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The Behaviour of Crude Oil Spilled under Multi-year Ice

Technology Development
Report EPS 4-EC-82-4

Environmental Impact Control Directorate
August 1982

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THE BEHAVIOUR OF CRUDE OIL SPILLED UNDER MULTI-YEAR ICE

by

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for the

Environmental Emergency Branch
Environmental Impact Control Directorate
Environmental Protection Service
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ABSTRACT

In June 1978, a total of 1.8 m^3 of Norman Wells crude oil was discharged at three locations under a multi-year ice cover in Griper Bay, Northwest Territories.

The test sites were overflown several times during the summer of 1978. A considerable amount of oil was found on the ice surface and a crack was observed, which passed through one of the test sites.

This report describes the results of a site investigation that was carried out during September 1979, at which time the fate of the spilled oil was determined.

The three sites were cored and drilled and the quantity of oil remaining in the ice sheet was estimated. Samples of surfaced oil and oil within the ice sheet were collected and analyzed to obtain estimates of the amount of weathering the oil had undergone.

Only a small amount of the oil which was originally discharged was still remaining in the ice sheet. A maximum of 10% of the oil originally discharged was found in the ice sheet at one site, while the other two sites had only 1% and none of the oil remaining.

Oil on the ice surface was severely weathered with an average weight loss (by evaporation) of more than 42%.

It was found that the oil had migrated horizontally within the ice sheet as well as vertically. The test sites still containing oil within the ice sheet had experienced a 400% increase in area of contamination over that originally occupied by the initial discharge.

The test site was relatively free of oil and it appeared that the natural processes of dispersion and evaporation had been relatively effective in cleanup.

RÉSUMÉ

En juin 1978, on a déversé un total de 1,8 m^3 de pétrole brut de Norman Wells à trois endroits différents sous une couverture de glace de plusieurs années dans la Baie Griper (Territoires du Nord-Ouest).

On a survolé les sites d'expérimentation plusieurs fois pendant l'été de 1978. On a vu une quantité considérable de pétrole à la surface de la glace et on a observé une crevasse traversant un des sites d'expérimentation.

Le présent rapport décrit des résultats d'une recherche sur place effectuée en septembre 1979, où le sort du pétrole déversé à été déterminé.

On a pris des carottes et effectué des forages aux trois endroits et on a estimé la quantité du pétrole restant dans la nappe de glace. On a prélevé et analysé des échantillons de pétrole se trouvant à la surface et à l'intérieur de la nappe de glace pour évaluer le viellissement subit par le pétrole.

Une petite partie seulement du pétrole déversé originalement se trouvait encore dans la nappe de glace. À un des sites on a trouvé un maximum de 10% du pétrole déversé alors qu'aux deux autres sites on ne trouvait plus que 1% et 0% du pétrole original.

Le pétrole se trouvant à la surface de la glace avait beaucoup vieilli et subi une perte moyenne de masse (par évaporation) de plus de 42%.

On a trouvé que le pétrole avait migré horizontalement et verticalement dans la nappe de glace. Aux sites d'expérimentation contenant encore du pétrole dans la nappe de glace la surface contaminée a augmenté de 400% par rapport à celle occupée originellement par le déversement.

Le site expérimental était relativement exempt de pétrole et il semble que les processus naturels de dispersion et d'évaporation ont produit un nettoyage assez efficace.

FOREWORD

The information in this report was compiled by G. Comfort and W. Purves of Arctec Canada Ltd. for the Environmental Protection Service. Peter Blackall of EPS acted as scientific authority.

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SUMMARY

The experimental spill program at Griper Bay, N.W.T., was undertaken to investigate the interaction of crude oil with multi-year ice, under the auspices of the Arctec Marine Oilspill Program (AMOP).

A total of 1.84 m^3 of Norman Wells crude oil, equally distributed between three different sites, was originally discharged under multi-year ice on June 1, 1978. The area was overflown during the 1978 summer and a considerable amount of oil was observed on the ice surface. A large crack was observed, which crossed the area of Site No. 3. Site visits were made in October 1978 and March 1979. Due to problems with logistics and weather, these missions failed to conclusively identify the test sites and to determine the amount of oil still trapped within the ice.

This report describes the results of a field investigation of September 9 to 18, 1979. The three sites were relocated and then drilled and cored to determine the amount of oil within the ice. Oil was found in the ice at Sites No. 1 and No. 2 ($\simeq$ 1% and 10% of the total volume of spilled oil, respectively). No significant amounts of oil were found within the ice at Site No. 3. Oil was on the surface and bottom of the ice, however, in the vicinity of the crack crossing Site No. 3.

The test site had frozen over when the field crew arrived. The melt pools had 5-15 cm of new growth, and fresh snow covered the site. Consequently, it was not possible to estimate the quantity of oil on the surface. During general searches, though, very little was found.

Several oil samples were taken for gas chromatographic analysis. Surface samples averaged more than 42% evaporation by weight. Samples taken of oil trapped within the ice were considerably fresher.

Further site visits should be made in the next melt season to investigate the long-term persistence of the oil still trapped within the ice sheet, and to assess the deleterious environmental effects of allowing natural processes (i.e. dispersion and evaporation) to clean up small oil spills.

CONCLUSIONS AND RECOMMENDATIONS

It is not possible to determine how much oil has surfaced from each spill site during the two summers to which each has been exposed (1978 and 1979), as data were not obtained in the fall of 1978. However, from the results of the September 9, 1979, site visit, it is clear that only a small amount of oil (less than 10% of that originally discharged) still remained in the ice sheet. The implications of this to oil spill contingency planning must be defined further, but it appears that an effective cleanup technique would be a well-timed visit (e.g. late in the first summer after the oil spill has occurred) when in situ burning could be attempted. If this technique had been used for the spill sites at Griper Bay, 90% of the spilled oil (assuming a burn efficiency of 100%), might have been cleaned up. Alternatively, the approach of letting the oil surface, disperse, and evaporate (as has been the case for the Griper Bay spill site) should be considered for small spills. If the environmental effects of this latter approach are not too deleterious, it may be most prudent and cost-effective not to clean up the spilled oil.

We recommend that the following efforts should be made to continue the experiment:

1) The site should be revisited during the summer of 1980. This should be scheduled for August to allow an estimate to be made of the quantity of oil that has surfaced. Sites No. 1 and No. 2 should be drilled and cored again to establish the quantity of oil remaining in the ice sheet. This will allow some estimate to be made of the long-term persistence of the oil within the ice sheet.

2) Measurements of the albedo of the test site should be made during this site visit to gain some understanding of the relationship of the amount of oil in the ice versus the change in heat budget. In this way, it may be possible to estimate the deleterious environmental effects of relying on natural processes (dispersion and evaporation) to clean up small oil spills.

3) Surface oil samples should be collected and their components analyzed to determine if aging has created any new by-products, which could increase toxicity.

1 INTRODUCTION

Continued exploratory drilling in the Beaufort Sea has focussed attention on potentially serious oil pollution incidents in ice-covered waters. Many scenarios are possible, including the rupture of an undersea pipeline or a subsea well blowout, upon which the greatest attention has been focussed. According to the standard blowout scenario (Norcor, 1977), oil and gas could be released in a ratio of 1:100 by volume and much of this material could be trapped under the sea ice.

In response to this concern, several projects, including the recently completed Beaufort Sea Project, have been undertaken to determine the behaviour and fate of oil spilled under an ice cover and to develop methods for oil spill cleanup. To date, the most extensive series of tests to determine the behaviour of oil under sea ice has been the large Norman Wells crude oil discharges in 1974-75 at Balaena Bay, N.W.T. (Norcor, 1975). Further studies have attempted to statistically determine the behaviour and fate of an oil spill in the Beaufort Sea shear zone with a matrix of drifting first-year and multi-year ice (Norcor, 1977). Other laboratory tests (ARCTEC, 1979; Chen et al., 1976; Mackay, et al., 1979) have examined the spreading of Norman Wells crude oil under smooth freshwater ice and the interaction of oil and gas under a saline ice cover. Further field studies have attempted to estimate the porosity of multi-year ice in summer time conditions and to infer the behaviour of an oil lens under multi-year ice (Milne et al., 1977).

From these and several other studies, some understanding of the behaviour and fate of oil and gas spilled under a sea ice cover has been obtained.

At Balaena Bay, oil spilled under the static first-year sea ice cover rose to the under ice surface in a rapidly spreading plume (Norcor, 1975). Upon reaching the under ice surface, the oil spread laterally. The depth of oil in trapped pools depended somewhat on the under ice topography, but pools averaging 2 cm in depth were found. These pools rapidly became immobilized (within a matter of hours) and were incorporated into the growing ice sheet. With the coming of spring, the ice sheet became sufficiently porous that the oil, encapsulated in lenses over the winter, began to migrate towards the ice surface using the channels left in the ice by draining brine during the growth of the sheet. Most of the oil surfaced in this manner before the sheet completely decayed. The surface oil collected on melt pools and the bulk of the cleanup was carried out by <u>in situ</u> burning

of the oil on the melt pools and burial of the residue. It was estimated that a significant amount of oil was also lost due to evaporation.

The results of this study were encouraging. They showed that spilled oil would be immobilized by the ice in lenses that would be released with warming of the ice sheet and that the ice cover could be used as a platform from which cleanup operations could be undertaken.

One of the major questions left unanswered by the Beaufort Sea Project, however, was the behaviour and fate of oil spilled under multi-year ice. Consequently, an AMOP-sponsored field program, consisting of a crude oil discharge under a multi-year ice cover in Griper Bay, NWT, was undertaken on June 1, 1978 (see Figure 1).

1.1 Synopsis of Oil Behaviour to Date at the Experimental Spill Site

A total of 1.84 m^3 (405 gallons) of Norman Wells crude oil was discharged under the ice at three different sites (0.61 m^3 (135 gallons) at each site). The ice thickness varied from 2.5 to 2.9 m and was at least second-year ice.

Figure 2 shows the layout of the test sites and the configuration of the oil pools that occupied under ice depressions initially after discharge of the oil in June 1978. Maximum oil pool thicknesses were measured and are indicated in Figure 2. The position of the pools were determined by chaining the distance from the dive hole to each spill site and estimating the bearing.

At that time, the mean snow depth at Site No. 1 was 1.41 m, and 1.46 m at Site No. 2. Site No. 3 was wind blown with only small pockets of snow.

The test area was overflown on June 13, 1978. There was no evidence of oil on the surface at that time. The next overflight of the test area was on July 1, 1978. Again, there was no evidence of oil at Sites No. 1 and No. 2. However, there was a large crack running through Site No. 3 and oil was observed on adjacent melt pools.

The test site was next overflown on August 20, 1978. Plates 1 and 2 show test site conditions at that time. Oil appeared to have surfaced, but not spread, at Sites No. 1 and No. 2, while considerable oil was visible on the surface in the vicinity of Site No. 3.

A site visit was made on October 13, 1978. Site No. 3 was cored and was found to contain oil only in the top 2 to 4 cm of the core. A core was taken from the ice in the vicinity of Site No. 1 but no evidence of oil was found. Site No. 2 was left unaltered for long-term monitoring. A 6 mm layer of oil was found at the top of the core, but the ice beneath the oil was found to be clean.The results of the gas chromatographic analysis done on samples collected during this visit are found in Appendix III.

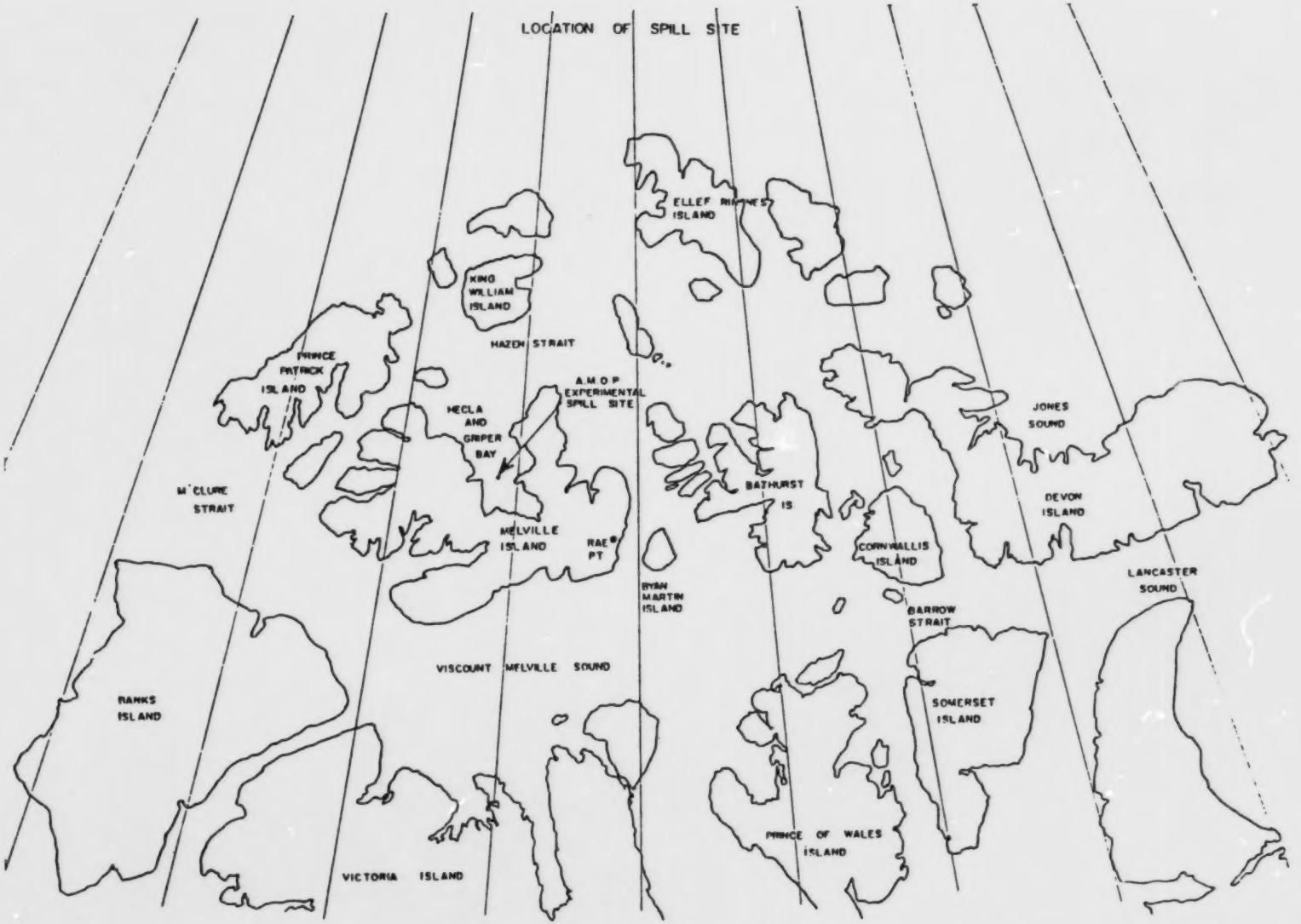

FIGURE 1 LOCATION OF SPILL SITE

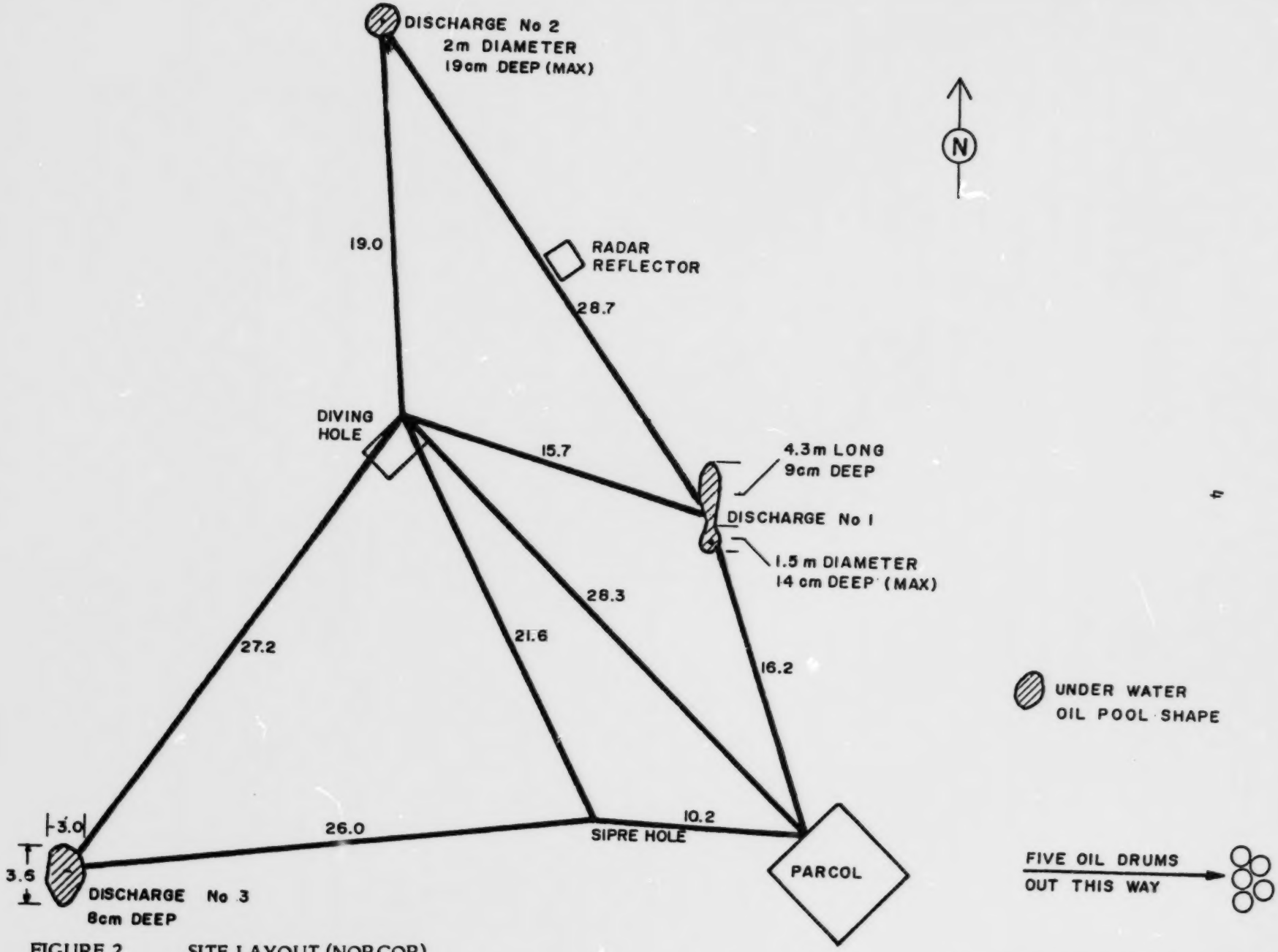

FIGURE 2 SITE LAYOUT (NORCOR)

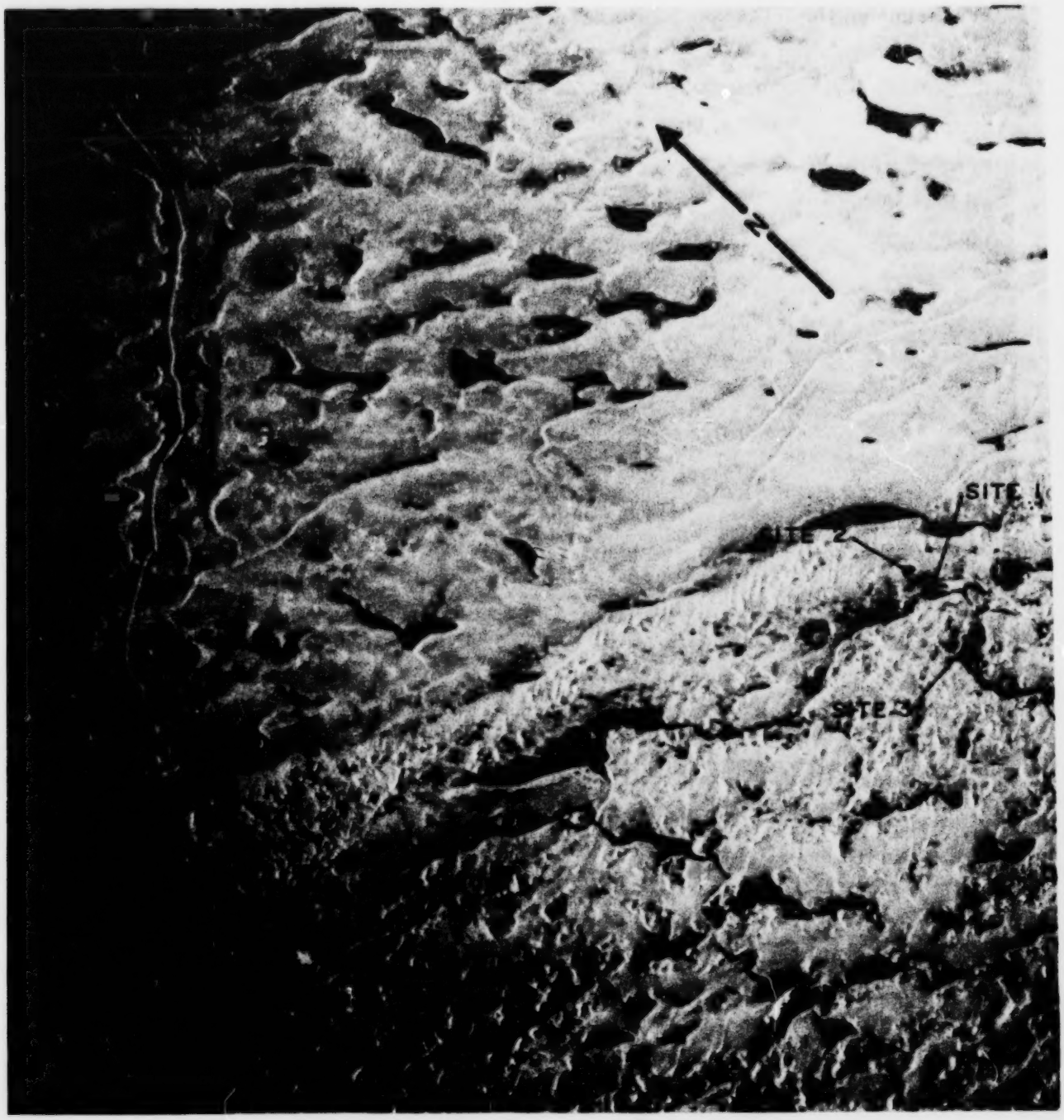

PLATE 1 VERTICAL AERIAL PHOTO OF SPILL SITES - August 20, 1978

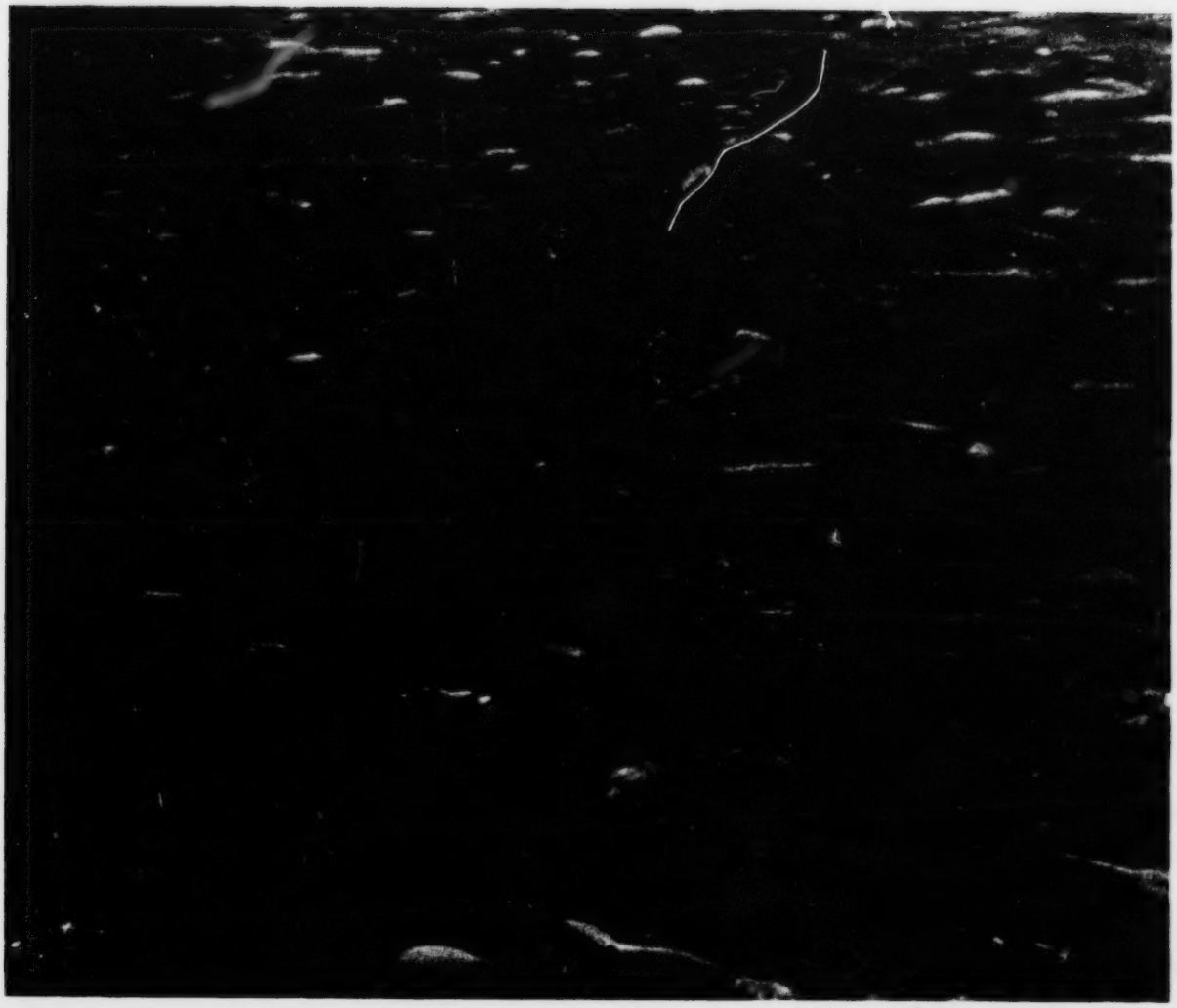

PLATE 2 OBLIQUE AERIAL PHOTO OF SPILL SITES - August 20, 1978

A second site visit was made on March 29, 1979. Site No. 3 was extensively drilled and no oil was found within the ice sheet . Site No. 2 was again left unaltered, and oil was not visible on the surface of the spill site. Results of the gas chromatographic analysis done on samples collected during this visit, are also found in Appendix III.

The Griper Bay experimental oil spill site was next occupied from September 9 to 18, 1979, by a field crew comprised of two Arctec Canada Ltd. personnel and two Environment Canada representatives. In this report, site conditions at that time are described in detail, and attempts to draw some conclusions as to the behaviour and fate of oil spilled under multi-year ice are made.

2 SURVEY TECHNIQUES

The Griper Bay experimental field camp was occupied by a four-man field crew from September 9 to 18, 1979. Bad weather conditions (poor visibility and fog) at the site forced the field crew to remain on site longer than the planned four-day period.

Upon arrival, no evidence of oil on the surface of any of the three test sites could be found. Some fresh snow had fallen and the melt pools had a crust of 5-15 cm of new ice. Several other melt pools had drained leaving a hummocked ice pattern. The parcol left on site by the previous field crews was in a very poor state of repair, due to the differential melt (in the order of 1 m) that had occurred between the centre of the parcol and the outside edges.

The test sites were located by chaining distances from the radar reflector and the parcol. These distances were scaled from the air photo taken August 20, 1978 (Plate 1). The positions of test Sites No. 1 and No. 2 were confirmed by drillholes. Site No. 3 was positively located during the initial survey by the thin ice (which was found to be unable to support the weight of a man) near it that had formed over the large crack, seen during the overflights of 1978.

The area of oiled ice was measured by drilling on a closely spaced grid pattern and observing whether the cuttings were oiled. The volume of oil in the ice at each site was determined by taking several ice cores. The samples were then melted down and after the oil had been separated using a benzene extract, the mass of the water and oil was measured. The density of representative oil samples was measured to allow calculation of oil volume. The salinity of the ice at test Sites No. 1 and No. 2 was also profiled from the cores taken.

In addition to the ice samples collected, several oil samples (surface and oiled ice) were obtained and analyzed using gas chromatographic techniques to assess the degree of weathering. These analyses and the oil mass measurements were undertaken by Professor D. Mackay of the University of Toronto. Appendix II provides his detailed description of the oil sample analysis techniques used. It is believed that the final accuracy of the oil mass measurements is approximately 10%.

The degree of weathering of the 12 oil samples analyzed was estimated by comparing each sample's gas chromatogram with a series of gas chromatograms prepared for Norman Wells crude oil with different degrees of weathering, i.e. 0; 6%; 12%; 20.4%; 29%; 36.7% and 43.2% weight loss by evaporation.

3 SURVEY RESULTS

3.1 Site Description

On September 9, the area had begun to freeze up and the melt pools were covered with 5-15 cm of new ice growth. Some snow had fallen and no oil was visible on the surface of any of the three spill sites. The only oil visible on the surface was traces of oil on the sides of a large drained melt pool southeast of the parcol. Consequently, it was not possible to determine the quantity of oil that had surfaced during the summer of 1979.

As discussed in Section 2, the spill sites were located from the air photo taken on August 20, 1978 (Plate 1). Figure 3 shows the location of the spill sites in relation to the parcol and the radar reflector. A comparison of Figures 2 and 3 shows that the positions of the spill sites, determined at the time of the oil discharge (June 1, 1978), were probably erroneous. This may have contributed to some of the difficulties encountered by previous investigators in locating the oil spill sites.

Conditions at Site No. 1

Site No. 1 was cored and drilled on September 11 to determine its area extent and the amount of oil remaining in the ice. Figure 4 describes the coring program that was carried out. Plate 3 depicts the surface conditions at Site No. 1.

Of the four cores taken at Site No. 1, only two contained sufficient oil to warrant taking a sample of the oiled ice. Each of the cores taken is described in Appendix I. Plates 4 to 6 depict the most heavily oiled cores (Cores No. 3 and No. 4). Core No. 4 was more heavily oiled than Core No. 3. Core No. 3 contained what appeared to be the remains of an oil lens at approximately 1.1 m depth. The remainder of the core was free of oil. Core No. 4 also exhibited an oil lens at the same depth but it also contained oil above the oil lens.

Table 1 lists the mass and volume of oil that was found in each core in Site No. 1. The volume occupied by the measured sample mass of oil was determined using an oil density of 0.88 g/cm^3. Table 2 lists the oil densities measured from the samples taken.

Conditions at Site No. 2

The coring and drilling program used at Site No. 2, to determine the area extent of oiled ice and the volume of oil in the ice, is illustrated by Figure 5.

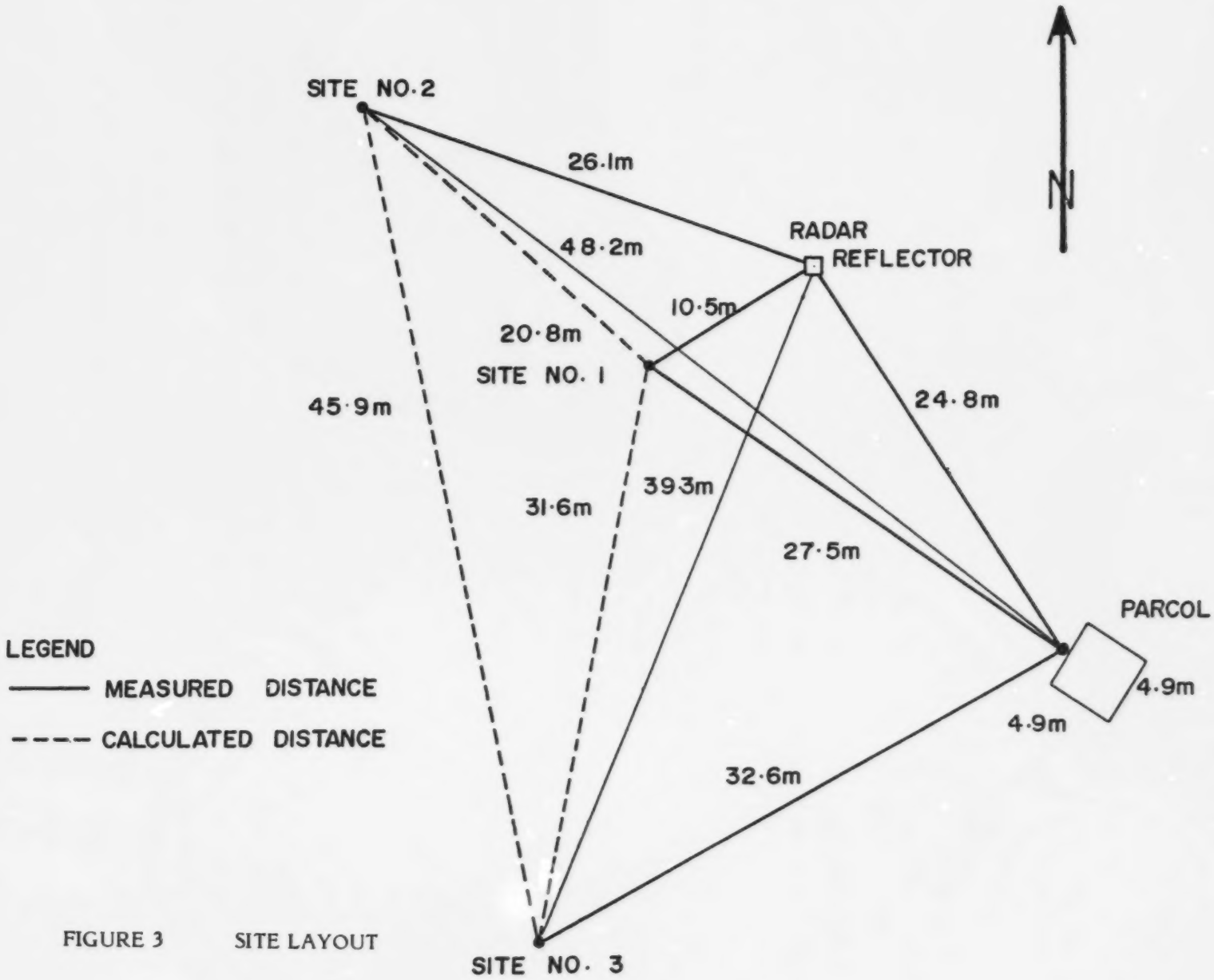

FIGURE 3 SITE LAYOUT

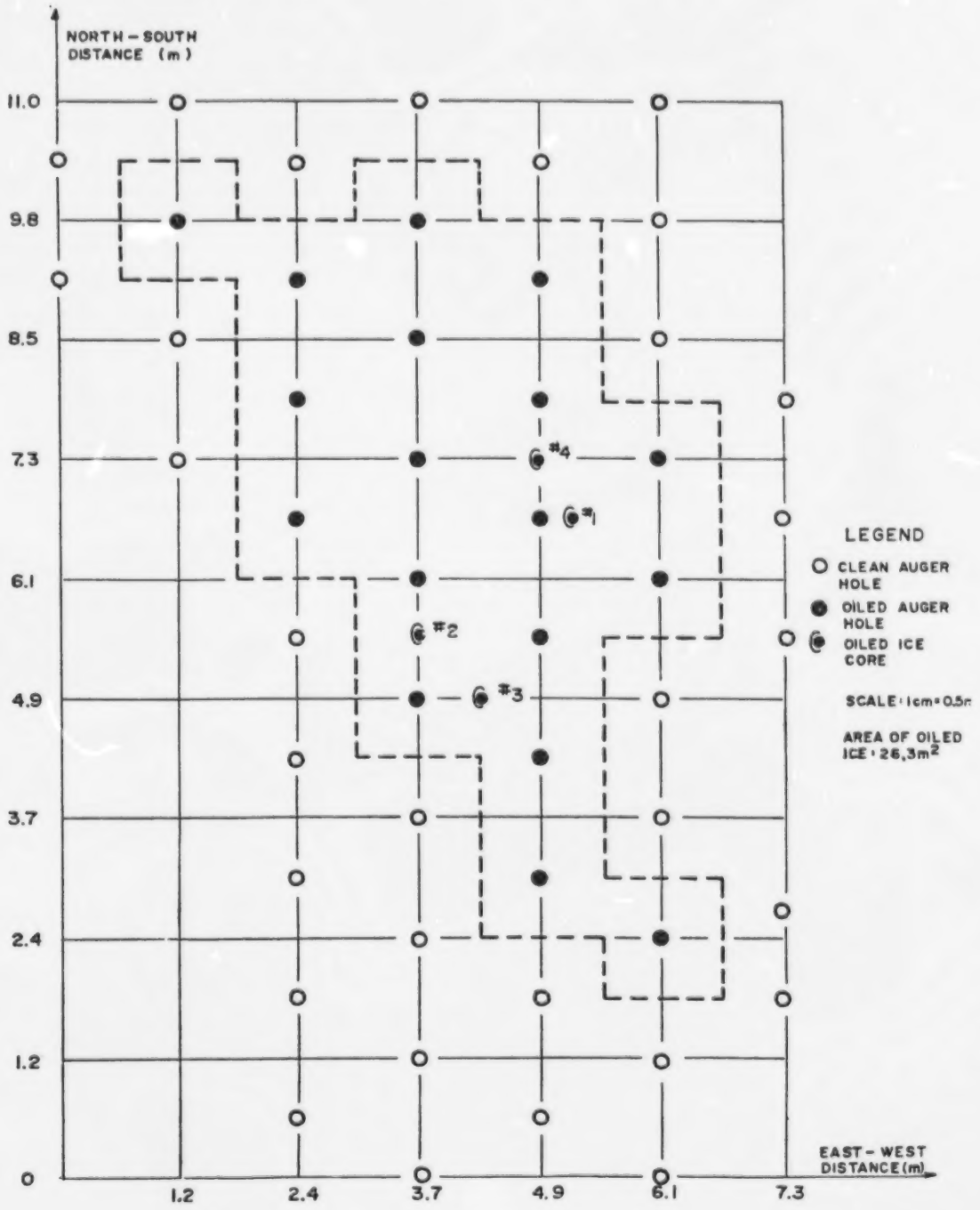

FIGURE 4 CORING PROGRAM - SITE NO. 1

PLATE 3 SURFACE OF SITE NO. 1

PLATE 4 CORE NO. 4 AT SITE NO. 1

PLATE 5 CORE NO. 3 AT SITE NO. 1

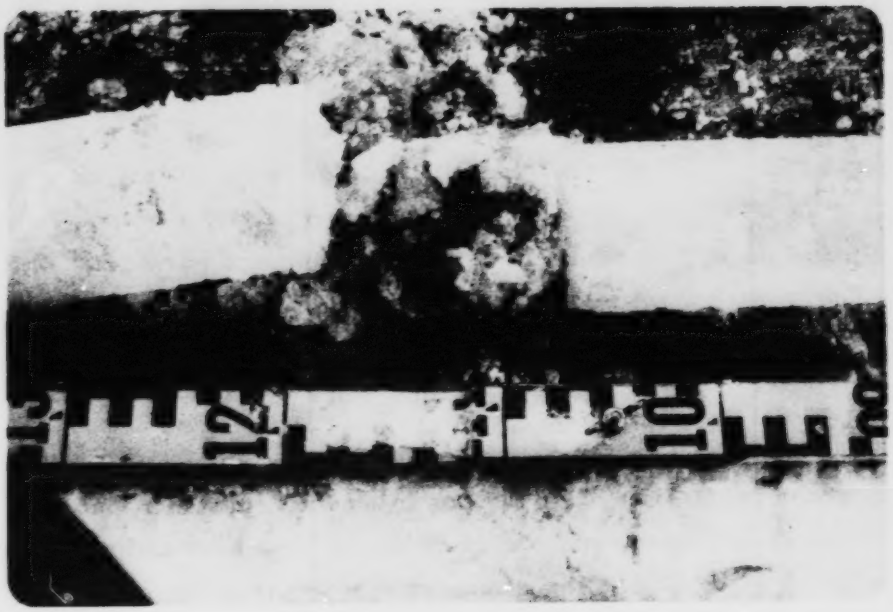

PLATE 6 OILED LENS IN CORE NO. 3 AT SITE NO. 1

TABLE 1 OIL IN ICE VOLUME -- SITE NO. 1

DATE: SEPTEMBER 11, 1979

Core No.	Sample No.	Sample Depth (m)	Total Core Length (m)	Oiled Core Length (m)	Mass of Oil in Sample (g)	Sample Volume of Oil (cm^3)	Volume of Oil in Core (cm^3)	Average % Oil in Core by Volume
1	-	-	1.95	-	-	-	0	0
2	-	-	1.9	-	-	-	0	0
3	25	1.0-1.1	1.9	0.1	0.46	0.40	0.40	0.0046
4	26-1	0-0.1	2.0	1.1	0.13	0.11	2.28	0.025
	26-2	0.5-0.6			0.12	0.11		
	26-3	1.0-1.1			0.38	0.33		
	27	1.1-1.2			0.32	0.28		
	26-4	1.5-1.6			0	0		
	26-5	1.9-2.0			0	0		

Mean: 0.0074

TABLE 2 OIL DENSITIES

Sample	Type and Location of Sample	Temp (°C)	Density (g/cm^3)
6	Core No. 5 -- Site No. 2 at 0.6 m depth	25	0.86
6	Core No. 5 -- Site No. 2 at 0.6 m depth	5	0.88
21	Surface sample of "mousse" in ice at Site No. 3	25	0.88
21	Surface sample of "mousse" in ice at Site No. 3	5	0.90

Two representative (in terms of concentration of oil) core samples (Cores No. 6 and No. 1-11) are depicted in Plates 7 to 10. Each of the cores taken is described in Appendix I, along with the salinity profiles conducted.

Core No. 6 was one of the most heavily oiled cores found in any of the experimental spill sites in Griper Bay. The mass and volume of oil in the oiled cores taken at Site No. 2 are listed in Table 3. Core No. 6 shows heavy staining throughout its length above the 1.7 m depth, except for the void space from 0.1 to 0.4 m which contained the 1979 melt pool growth. The bottom 0.5 m of the core is actually free of oil but shows contamination (from the core barrel) in Plate 7.

Plate 8 shows a heavy concentration of oil in the brine channels. This core was probably taken near where the depth of the discharged oil pool was the greatest.

Core No. 1-11, depicted in Plates 9 and 10, contains a moderate amount of oil. The oil is most heavily concentrated at approximately the 0.7 to 1.2 m depth. As can be seen from Appendix I, this general trend is apparent for most of the other cores taken at Site No. 2. It may be that this level represents the extent of oil migration in the ice during the summer of 1978. Most cores taken at Site No. 2 show a band of unoiled ice above the most heavily oiled portion. This may represent a new growth of ice on the melt pools formed during the 1978 summer.

Conditions at Site No. 3

Numerous holes were made and two cores were taken in the vicinity of Site No. 3. No significant amounts of oil were found, however, and it was not possible to define an oiled area of ice that was representative of Site No. 3.

Plate 11 depicts the surface conditions near Site No. 3. The illustrated hole was covered by a new growth of ice approximately 2-3 cm thick. There was a considerable amount of heavily weathered oil on the surface of the water. Plate 12 shows

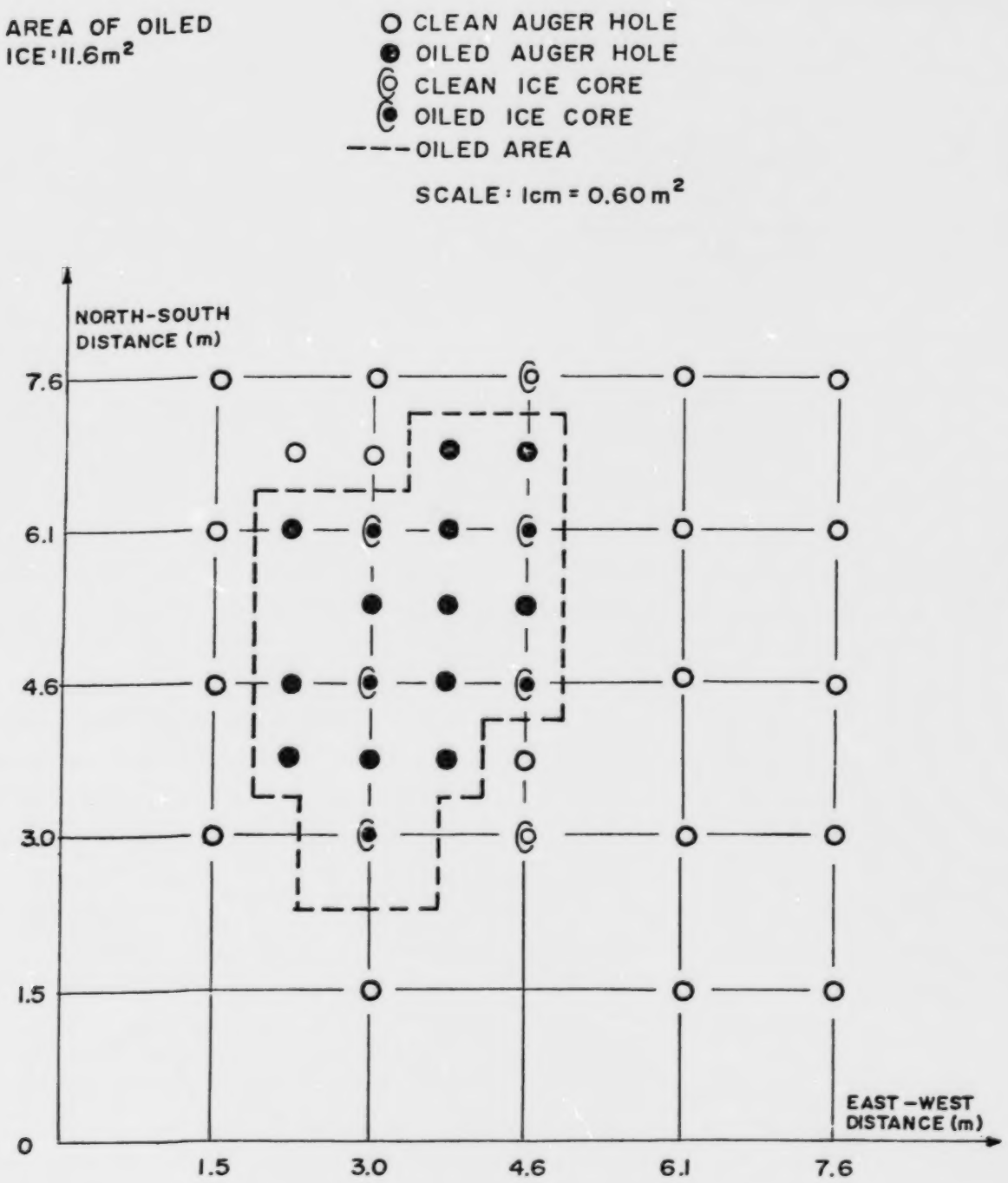

FIGURE 5 CORING PROGRAM - SITE NO. 2

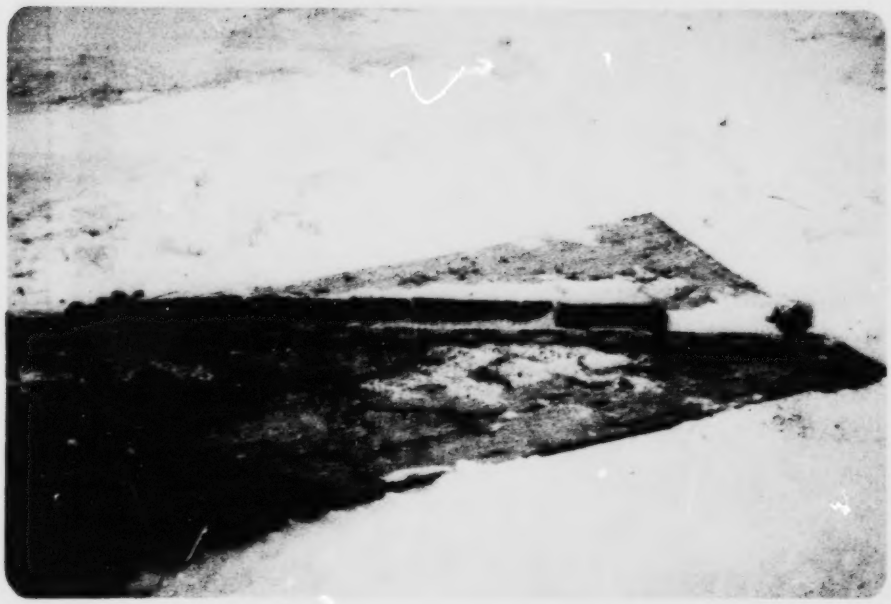

PLATE 7 CORE NO. 6 AT SITE NO. 2

PLATE 8 OILED BRINE CHANNELS IN CORE NO. 6 AT 1.0 m DEPTH

PLATE 9 CORE NO. 1-11 AT SITE NO. 2

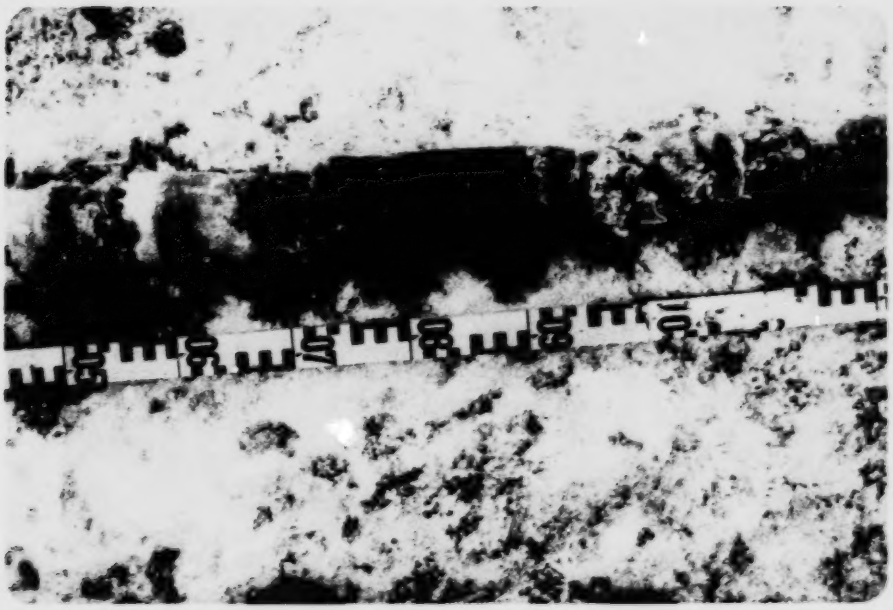

PLATE 10 CLOSE-UP OF HEAVILY OILED PORTION OF CORE NO. 1-11

TABLE 3 OIL IN ICE VOLUME -- SITE NO. 2

DATE: SEPTEMBER 10-11, 1979

Core No.	Sample No.	Sample Depth (m)	Total Core Length (m)	Oiled Core Length (m)	Mass of Oil in Sample (g)	Sample Volume of Oil (cm^3)	Volume of Oil in Core (cm^3)	Average % Oil in Core by Volume
2	3	1.0-1.1	2.4	0.15	0.78	0.69	1.04	0.0095
3	4	0-0.1	1.8	0.4	2.67	2.35	9.4	0.11
5	6	0.6-0.7	1.8	0.2	4.23	3.72	7.4	0.09
6	8	0.5-0.6	2.5	1.8	6.96	6.12	68.8	0.60
	9	1.0-1.1			4.71	4.14		
	10	1.5-1.6			5.6	4.93		
	11	2.0-2.1			0.11	0.10		
7	12	0.5-0.6	2.4	1.9	0.25	0.22	67.0	0.61
	13	1.0-1.1			2.43	2.14		
	14	1.5-1.6			12.45	10.96		
	15	2.0-2.1			0.90	0.79		
1-11	28-1	0-0.1	2.55	1.7	0.0086	0.0076	8.4	0.072
	28-2	0.5-0.6			0.49	0.43		
	28-3	1.0-1.1			0.59	0.52		
	28-4	1.5-1.6			0.015	0.013		
	28-5	2.0-2.1			0.0075	0.0066		
	28-6	2.5-2.6			0.0043	0.0038		
	29	0.7-0.8			2.24	1.97		
								Mean: 0.25

a typical sample of the "mousse" that was present at Site No. 3. It is highly probable that the crack in the ice near Site No. 3 (first observed on July 1, 1978) crossed through the open hole shown in Plate 11.

Core No. 1 is illustrated in Plate 13. This core was taken near the open hole and shows no oiling, except for the bottom 10 cm, which contains a relatively high concentration of particulate weathered oil. It is unlikely that the severely weathered oil found in Core No. 1 is oil that has remained in the ice since the initial discharge on June 1, 1978. It is more probable that this material was carried beneath the ice by the vortex created by water draining from the melt pools during the summer of 1979. This is supported by the fact that the large hole shown in Plate 11 went through the ice sheet.

Core No. 2 was also very clean and oil-free except for one relatively large oil globule (1-2 cm in diameter) at a depth of 1.4 m. A description of Cores No. 1 and No. 2 is provided in Appendix I.

Table 4 shows the amount of oil that was contained in both cores. On the basis of the observations made during the September 9 site visit, it can be concluded that no significant amounts of oil are contained in the ice near Site No. 3.

Table 5 lists the overall volume of oil that was found in the ice at each site. At Site No. 1 it is likely that this quantity included oil that surfaced during the summer of 1979 and was refrozen into the ice sheet by the new growth of ice on the melt pools.

3.2 Degree of Weathering of the Oil

A total of 12 samples were selected for gas chromatographic analysis, in order to estimate the extent of weathering of the oil on the ice surface and within the ice sheet.

The gas chromatographic analysis program and test results are given in Table 6. The percentage of evaporation (by weight) of each oil sample, with respect to fresh Norman Wells crude oil, has been estimated by comparing the gas chromatograms of each sample to standard gas chromatograms for various degrees of evaporation (by weight) of Norman Wells crude. Figures 6 and 7 show the gas chromatograms for relatively fresh oil within the ice sheet and for a sample of "mousse", respectively. Figures 8 and 9 show two of the standard gas chromatograms (0% and 43.2% evaporation, by weight, respectively) used to determine the degree of weathering of each oil sample. A complete set of the oil sample gas chromatograms and the standards used during the analysis is provided in Appendix II.

PLATE 11 OPEN WATER AT SITE NO. 3

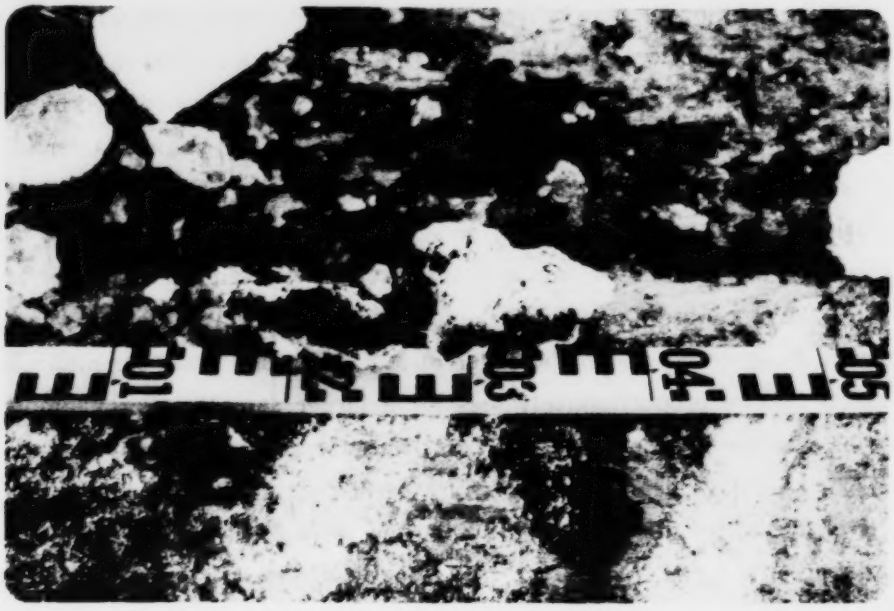

PLATE 12 SURFACE SAMPLE OF "MOUSSE" AT SITE NO. 3

PLATE 13 CORE NO. 1 AT SITE NO. 3

The oil samples have been divided into two main groups; surface samples, and oil-in-ice samples, to allow interpretation of the results (see Table 7).

As would be expected, the surface samples were more weathered than the samples of the oil taken within the ice sheet. The surface samples were exposed to the weathering processes of both evaporation and dissolution, while the oil in the ice was weathered mainly by dissolution. The surface samples ranged from being weathered by 37 to >43%, while the oiled ice samples ranged from being 12 to 20% weathered by weight.

As would be expected from small field tests, there is some scatter in the test results. This may be attributed to several factors including natural variability and the adverse conditions under which the tests were conducted and the samples collected. Evaporation loss of the oil sample into the air space in the sample container is another factor that could have caused an apparently high degree of weathering for small samples of fresh Norman Wells crude oil (in the order of 30% for a one gram sample). This error would be expected to be proportionately less for a larger sample. For example, a 10 g sample might be weathered to an extent of 3%. It is for this reason that Samples No. 25, No. 26-3 and No. 28-3 have been excluded from the analysis. The remainder of the oiled ice samples (No. 8, No. 9 and No. 10) were fairly large (4.7 to 7 g) and, hence, were less sensitive to this error source.

TABLE 4 OIL IN ICE VOLUME -- SITE NO. 3

DATE: SEPTEMBER 11, 1979

Core No.	Sample No.	Sample Depth (m)	Total Core Length (m)	Oiled Core Length (m)	Mass of Oil in Sample (g)	Sample Volume of Oil (cm^3)	Volume of Oil in Core (cm^3)	Average % of Oil in Core by Volume
1	20	0.95-1.05	1.1	0.1	1.63	1.43	1.43	0.029
2	23	1.4-1.5	2.4	0.1	0.061	0.054	0.054	0.00049
								Mean: 0.0147

TABLE 5 OVERALL VOLUME OF OIL IN ICE

Site No.	Area of Contamination (m^3)	Mean Ice Thickness (m)	Total Volume of Oiled Ice (m^3)	Volume of Oil in Ice (m^3)	% of Volume Oil Spilled in Ice
1	26.3	1.95	51.3	0.0038	≈ 1
2	11.6	2.24	26.0	0.065	10
3	-	-	-	-	-

TABLE 6 DEGREE OF WEATHERING OF THE OIL

Sample No.	Discharge No.	Type and Location of Sample	Estimated Mass % Evaporated
1	2	Oiled snow	>43
5	2	Surface "mousse" mixed with fresh snow	43
8	2	Core No. 6 at 0.50 m depth	20
9	2	Core No. 6 at 1.0 m depth	12-15
10	2	Core No. 6 at 1.5 m depth	20
17	-	Surface sample at Position 2 (33.53 m from radar reflector, 42.67 m from parcol)	43
18	3	Surface sample from open hole	37
22	3	Surface sample of "mousse" from open hole	37
25	1	Core No. 3 at 1.0-1.1 m depth[2]	43
26-2	1	Core No. 4 at 0-0.1 m depth[1]	43
26-3	1	Core No. 4 at 1.0-1.1 m depth[2]	40
28-2	2	Core No. 1-11 at 0-0.1 m depth[1]	43
28-3	2	Core No. 1-11 at 1.0-1.1 m depth[2]	40

Notes:

[1] These samples were considered as surface samples, since they represent new growth on the melt pools which has encapsulated oil that surfaced during the 1979 summer.

[2] These samples contained less than one gram of oil and, therefore, have not been included in the analysis.

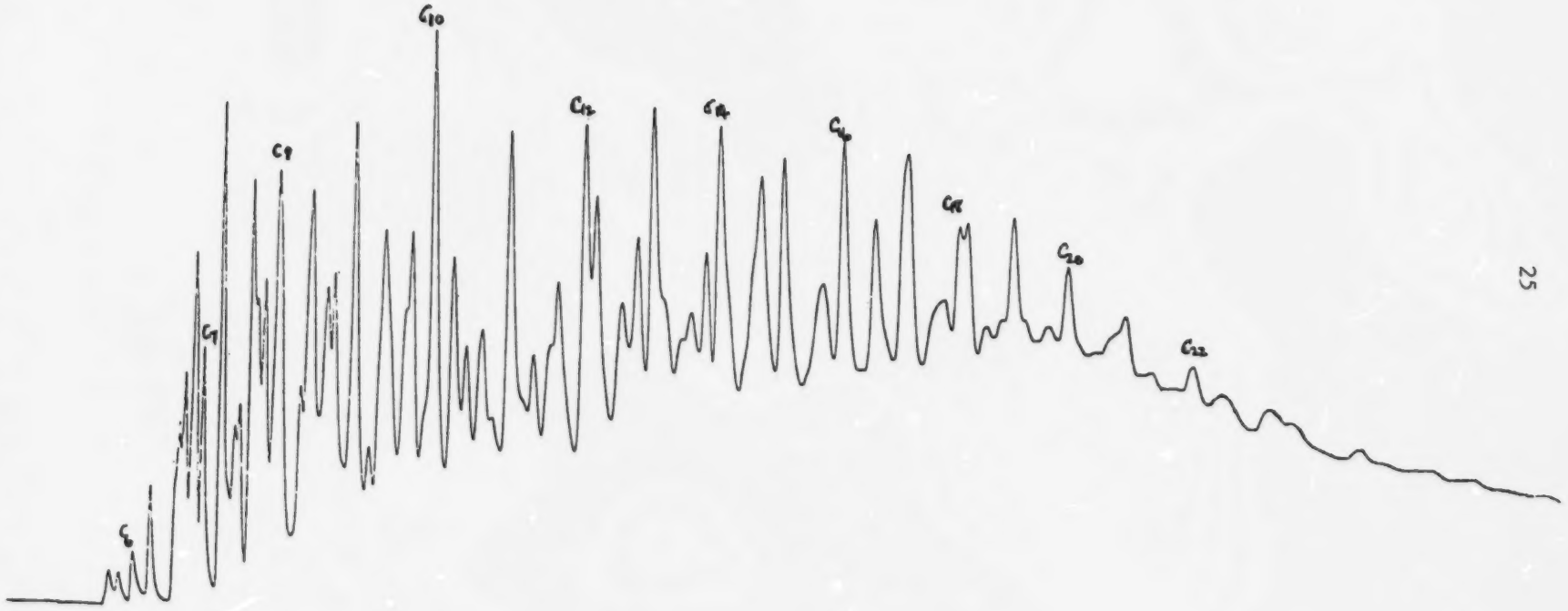

FIGURE 6 GAS CHROMATOGRAM FOR SAMPLE NO. 8; OIL IN ICE CORE NO. 6 AT 0.5 m DEPTH

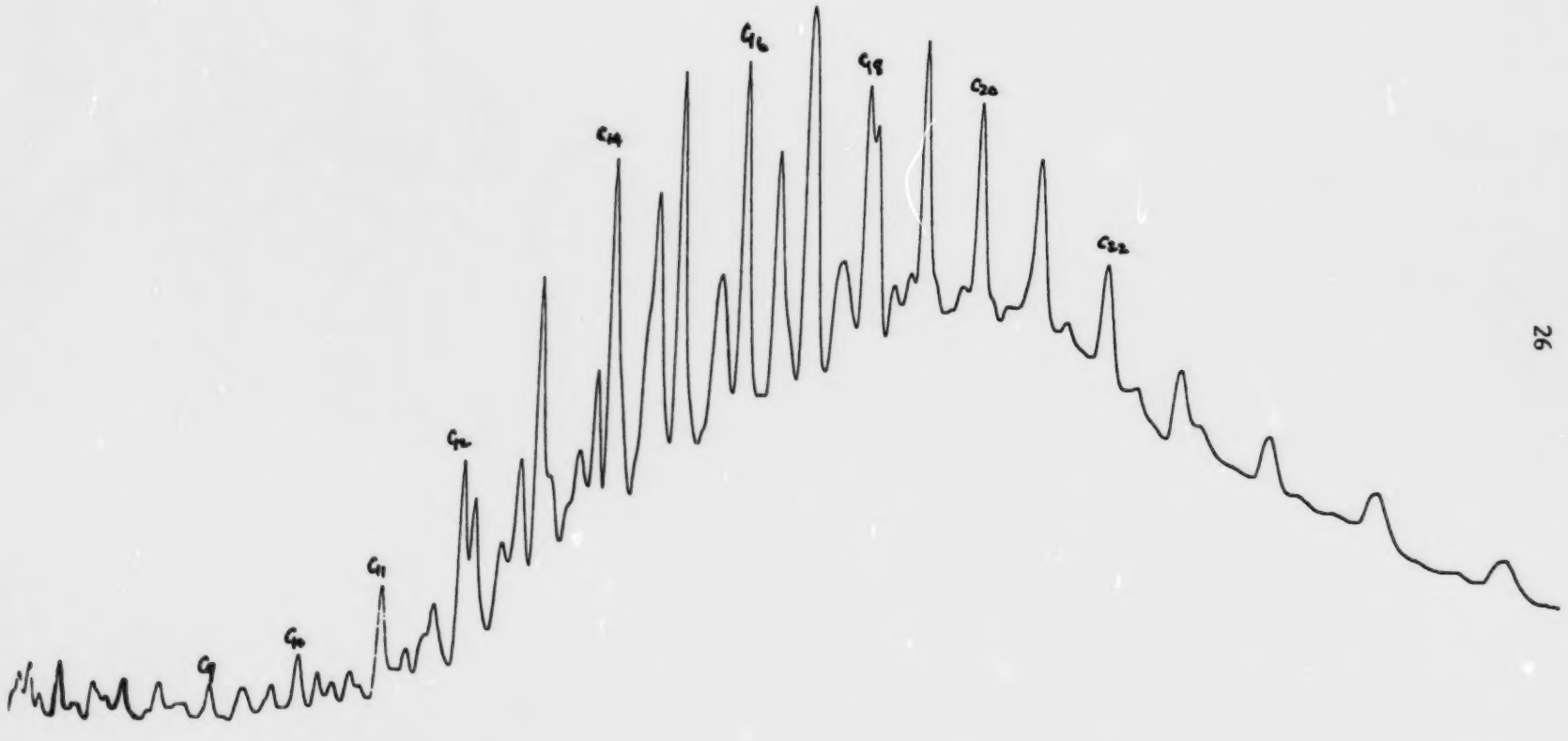

FIGURE 7 GAS CHROMATOGRAM FOR SAMPLE NO. 22; SURFACE SAMPLE OF "MOUSSE"

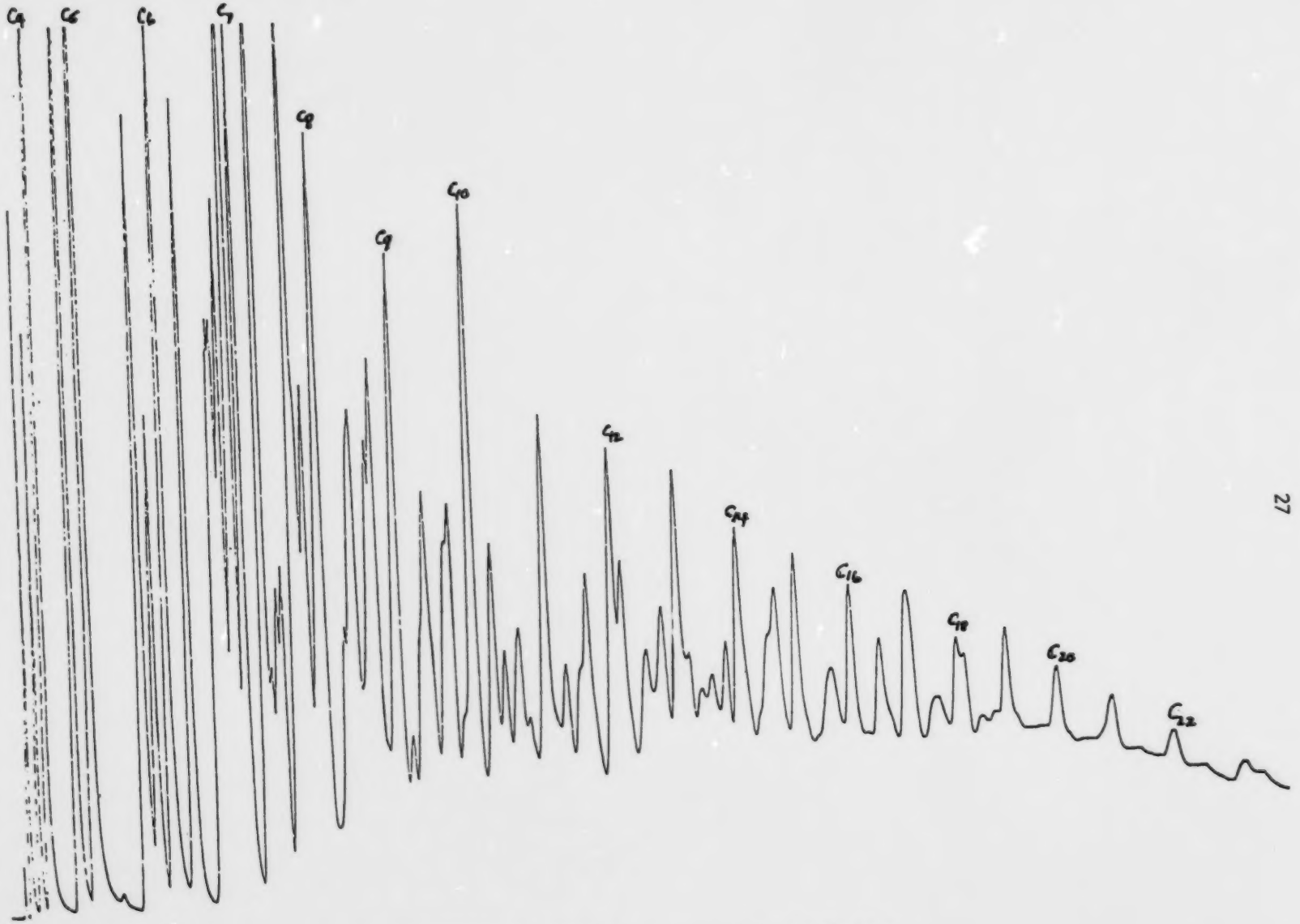

FIGURE 8 GAS CHROMATOGRAM FOR FRESH NORMAN WELLS CRUDE OIL (0% EVAPORATION)

FIGURE 9 GAS CHROMATOGRAM FOR NORMAN WELLS CRUDE OIL
(43.2% EVAPORATION)

TABLE 7 OVERALL ESTIMATED MASS PERCENT OF EVAPORATED OIL

Sample Type	Min.	Max.	Mean
Surface	37	>43	>42
Oil-in-Ice	12	20	17

On the basis of the gas chromatographic analysis, it is clear that significant weathering of the oil on the ice surface has occurred and the relatively low standard deviation (approximately 3%) indicates that the mean value can be used with some confidence.

However, the quantitative estimates of the extent of weathering of the oil within the ice sheet are less clear. It is probable that some weathering of the oil within the ice sheet has occurred. Since the test results agree with those expected, and in the absence of contradictory data, it is proposed that the test results be adopted for oil spill contingency planning purposes.

3.3 Oil Mass Balance

The results of the September 9 site visit indicate that only a small amount of the oil originally discharged still remains in the ice sheet. Table 8 lists the estimated oil mass balance.

It is impossible to verify the oil mass balance estimates presented in Table 8. The site visit was delayed until after the melt pools at the test site had frozen over and the test site had become covered with a fresh snowfall, making it impossible to measure the quantity of oil dispersed on the ice surface. However, from the test site photos of August 20, 1978 (Plates 1 and 2), it is clear that a significant amount of oil could have escaped from the test site area by wind action on interconnecting melt pools and through absorption by blowing snow. On August 20, 1978, a large oil slick on a melt pool southeast of the parcel was observed, and is visible in Plates 1 and 2.

The estimates of the oil still remaining within the ice sheet include some of the oil that had surfaced and was floating on the melt pools at the original spill sites at freeze-up. This encapsulated oil represents only a fraction of the total quantity of surfaced oil, however.

TABLE 8 OIL MASS BALANCE

Sites No. 1 and No. 2	m^3
Total Quantity Discharged:	1.2
Total Quantity Remaining in Ice:	0.07
Oil Losses Due to Dissolution (est. 15%):	0.01
∴ Total Quantity of Surfaced Oil:	1.1
Oil Losses Due to Weathering (est. 43%)	0.5
∴ Total Quantity of Oil Dispersed on Surface:	0.6
Site No. 3	
Total Quantity Discharged:	0.6
Total Quantity Remaining in Ice:	0.0
Oil Losses Due to Weathering (est: 43%)	0.3
∴ Total Quantity of Oil Dispersed on Surface:	0.3

3.4 Test Site Behaviour

Considerable variation in the behaviour of the oil at the three test sites has been observed. This may be due to local differences at each test site.

Most of the oil discharged at test Site No. 3 has probably surfaced due to the crack that penetrated the spill site area last summer. This oil has probably been dispersed on the melt pools and evaporated during the past two summers.

Sites No. 1 and No. 2 both contain a small amount of oil in the ice. However, more oil still remains in the ice at Site No. 2 than at Site No. 1 (i.e. ≈10% vs ≈ 1% of the total spilled oil volume). The oiled area at Site No. 1 is approximately 2.3 times as large as that at Site No. 2. This corresponds reasonably well with the ratio of the estimates of underwater oil pool areas for the two sites (6.1 m^2 for Site No. 1 versus 3.1 m^2 for Site No. 2 - area ratio of 2.0 m^2 between sites). For both sites, the area of oiled ice is greater than the area of the underwater oil pool by approximately 400%.

It is not clear why Site No. 2 had more oil still trapped in the ice than did Site No. 1. Ice thicknesses at Site No. 2 were approximately 10% greater than at Site No. 1.

Therefore, the oil would have had to travel a greater distance through the ice sheet to surface at Site No. 2, and oil migration may have been sufficiently retarded over the short summer that a significant difference was created.

As well, the configuration of the underwater oil pools at each site was quite different, as can be seen from Figure 2. The oil pool at Site No. 2 was deep and confined while the oil pool at Site No. 1 occupied a larger area. It may be that only a finite rate of oil flow through the multi-year brine channels is possible and conditions at Site No. 2 have exceeded the capacity of the ice sheet to allow the migration of oil to the surface.

Other factors, such as the natural variability of the ice sheet and snow cover, also come into play and may have influenced the results of these experiments.

It is difficult and probably incorrect to attempt to infer the interaction of crude oil with multi-year ice by selecting one of the three test spills as being typical. Perhaps each spill was not large enough to avoid being significantly influenced by natural variations in the ice and snow cover.

A large oil spill would contaminate a large area of ice that would encompass all three observed patterns of behaviour. Therefore, the differences observed between the three sites at Griper Bay represent a measure of the range of behaviour that is possible.

It is felt that the results of these tests should be viewed in perspective with the overall objective of the research program.

Although the three spill sites have exhibited dissimilar behaviour in terms of the mechanism of oil migration and the quantities of oil remaining in the ice, the end result has been essentially the same. At the end of two melt seasons, a maximum of 10% of the original volume of spilled oil was still in the ice.

It is this observation that probably has the greatest implications for oil spill contingency planning purposes.

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Mackay, D. et al., "Oil Spill Processes and Models-A Laboratory Study of the Behaviour of Oil and Gas Under Ice", Proceedings of the AMOP Technical Seminar, Edmonton, (1979).

Milne, A., R.H. Herlinveaux, and G. Walton, "A Field Study of the Permeability of Multi-year Ice to Sea Water with Implications on its Permeability to Oil", prepared for Environment Canada, EPS 4-EC-77-11, (1977).

Norcor Engineering and Research Ltd., "The Interaction of Crude Oil with Arctic Sea Ice", Beaufort Sea Project Report No. 27, (1975).

Norcor Engineering and Research Ltd., "Probable Behaviour and Fate of a Winter Oil Spill in the Beaufort Sea", Environment Canada, EPS 4-EC-77-5, (1977).

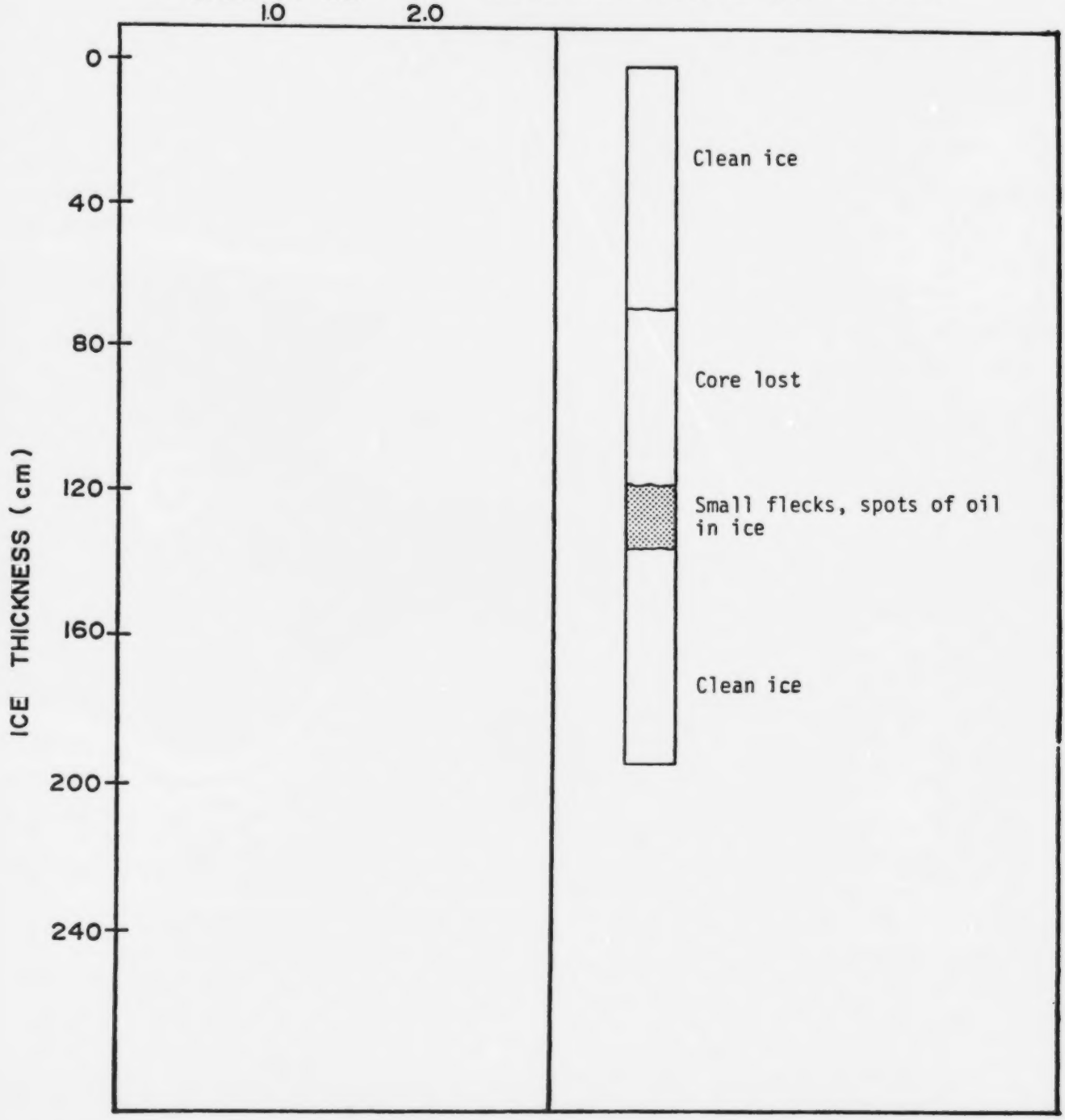
Purves, W.F., "The Interaction of Crude Oil and Natural Gas with Laboratory Grown Saline Ice", by Arctic Canada Ltd. for the Environmental Protection Service, Technology Development Report, EPS 4-EC-78-9, (1978).

APPENDIX I

ICE CORE REPORTS

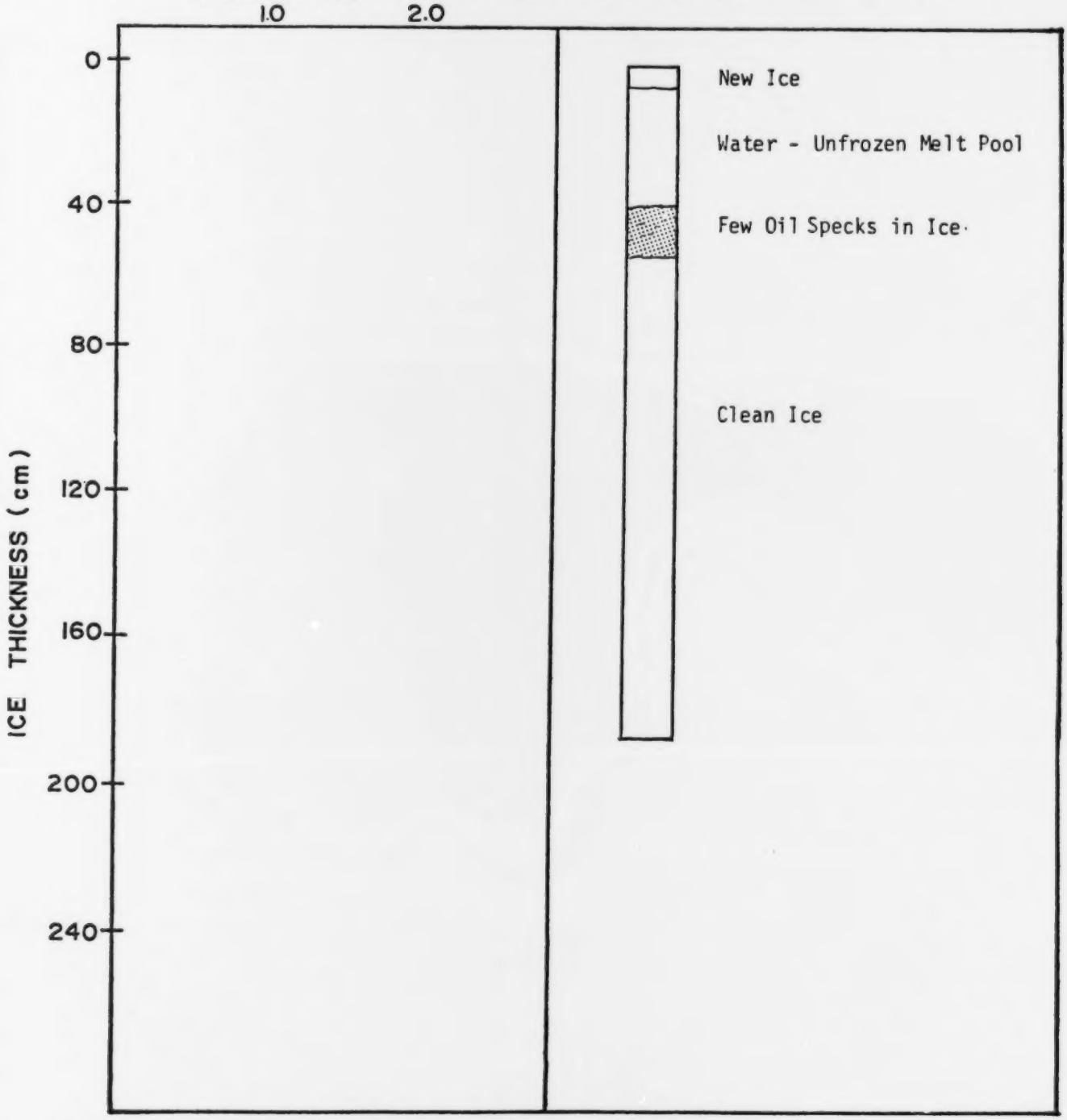
ICE CORE REPORT

DISCHARGE NO. 1
CORE NO. 1
DATE: Sept. 11, 1979
ICE THICKNESS: 1.95 m
ROLL NO. 2 PHOTO NO. 2-6 to 2-7



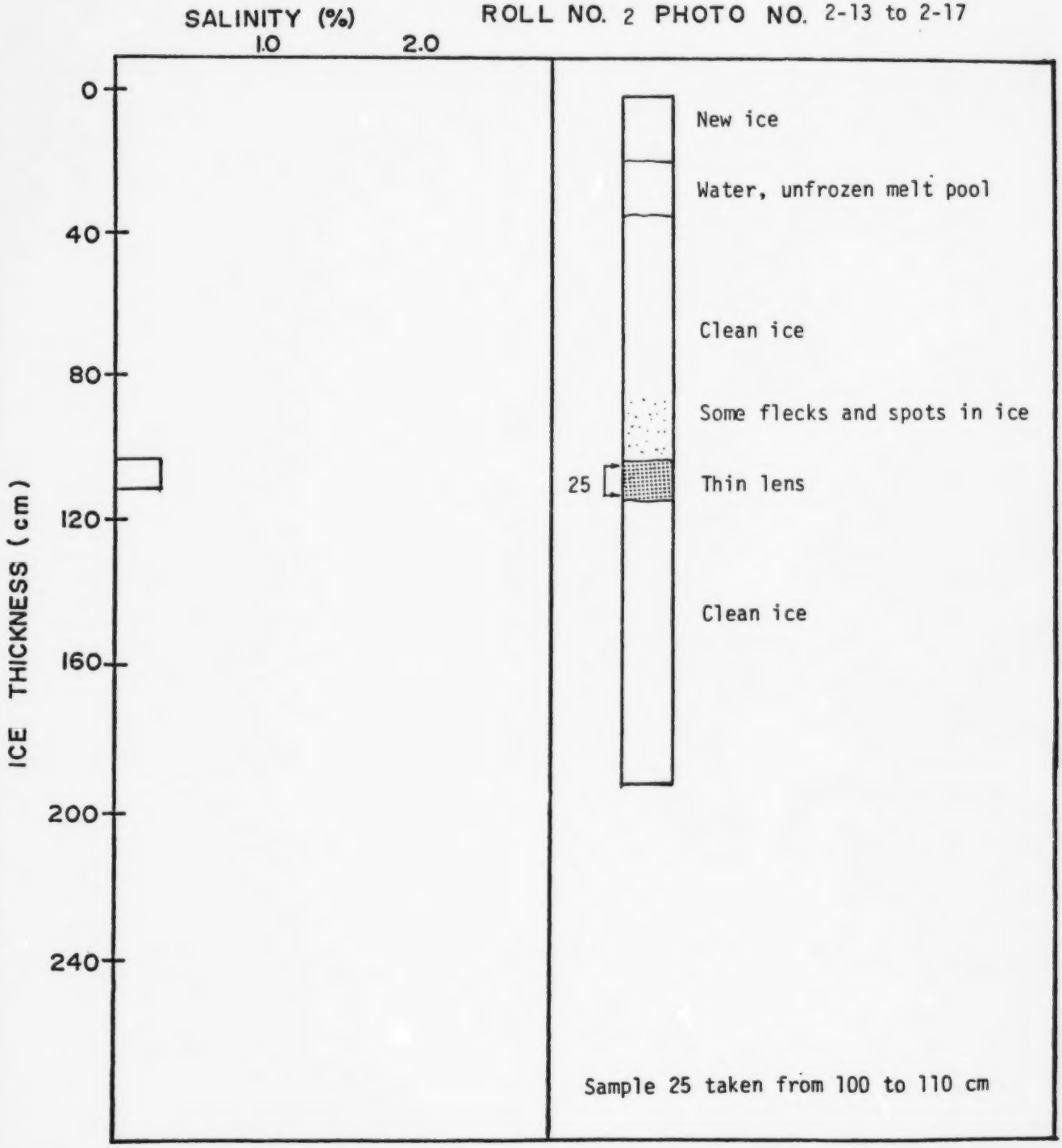
ICE CORE REPORT

DISCHARGE NO. 1
CORE NO. 2
DATE: September 11, 1979
ICE THICKNESS: 1.9m
ROLL NO. 2 PHOTO NO. 2-11, 2-12



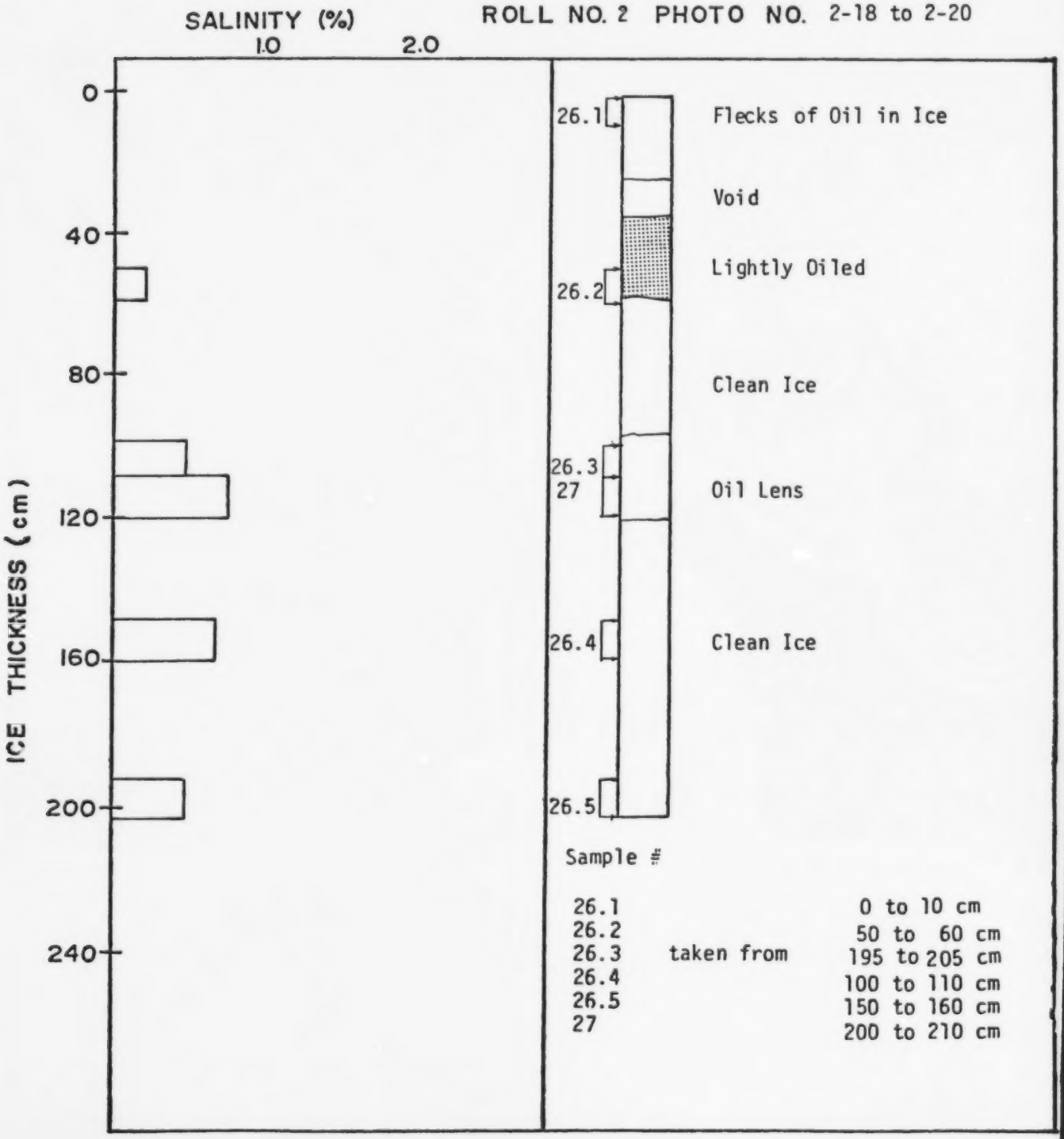
ICE CORE REPORT

DISCHARGE NO. 1
CORE NO. 3
DATE: Sept. 11, 1979
ICE THICKNESS: 1.95 m
ROLL NO. 2 PHOTO NO. 2-13 to 2-17



ICE CORE REPORT

DISCHARGE NO. 1
CORE NO. 4
DATE: September 11, 1979
ICE THICKNESS: 2.05m
ROLL NO. 2 PHOTO NO. 2-18 to 2-20

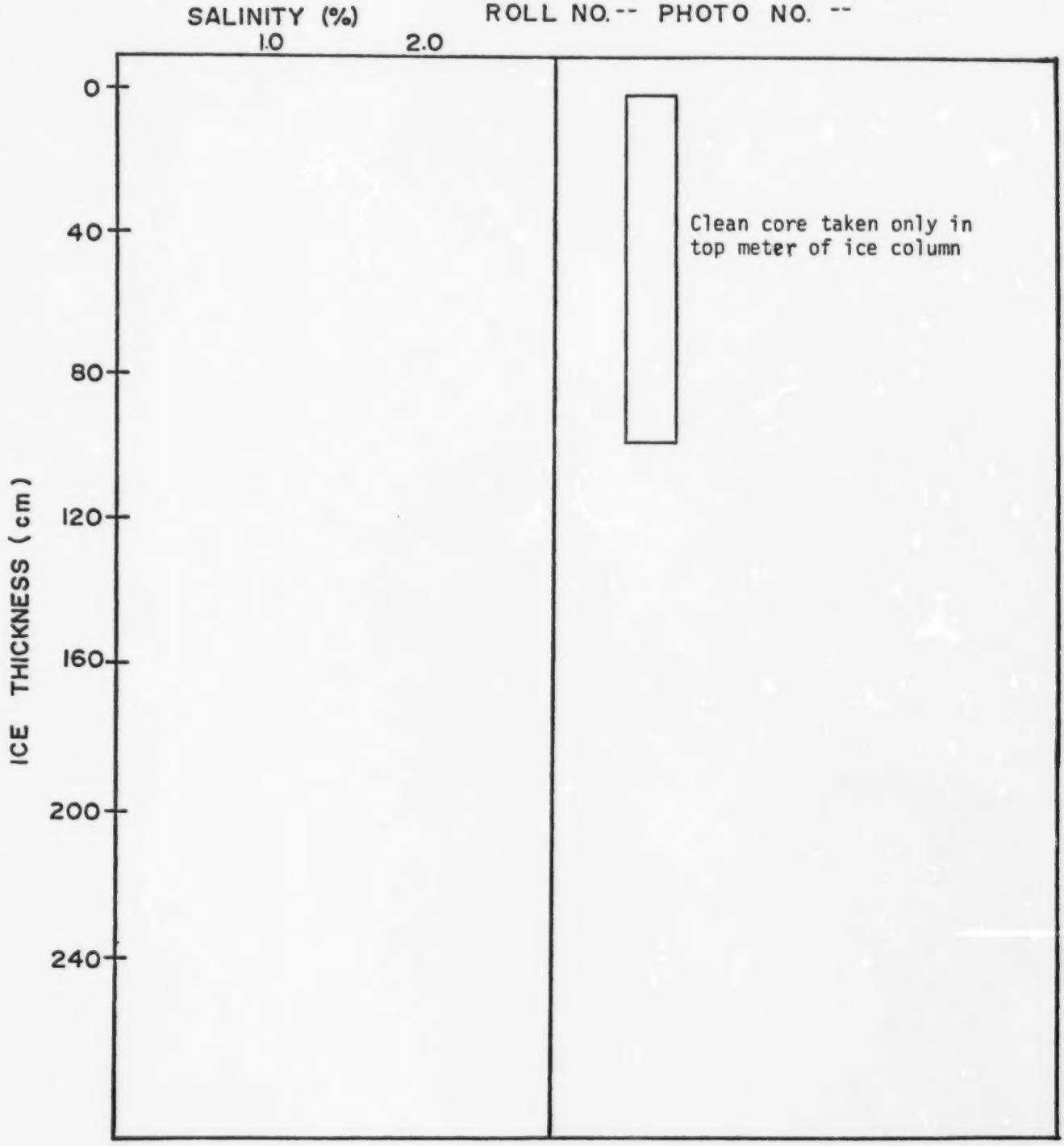


Sample #

26.1		0 to 10 cm
26.2		50 to 60 cm
26.3	taken from	195 to 205 cm
26.4		100 to 110 cm
26.5		150 to 160 cm
27		200 to 210 cm

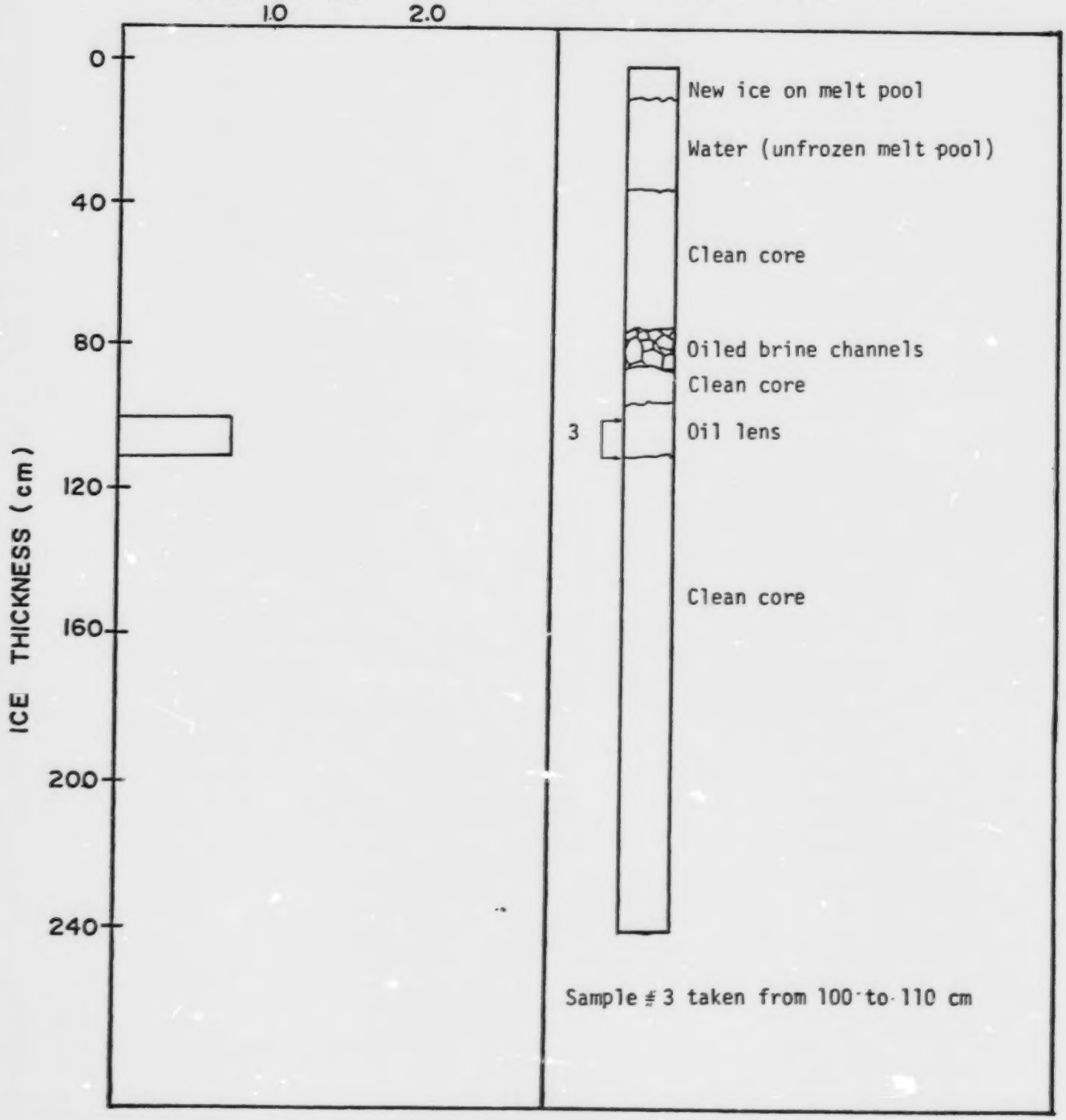
ICE CORE REPORT

DISCHARGE NO. 2
CORE NO. 1
DATE: Sept. 10, 1979
ICE THICKNESS: --
ROLL NO.-- PHOTO NO. --



ICE CORE REPORT

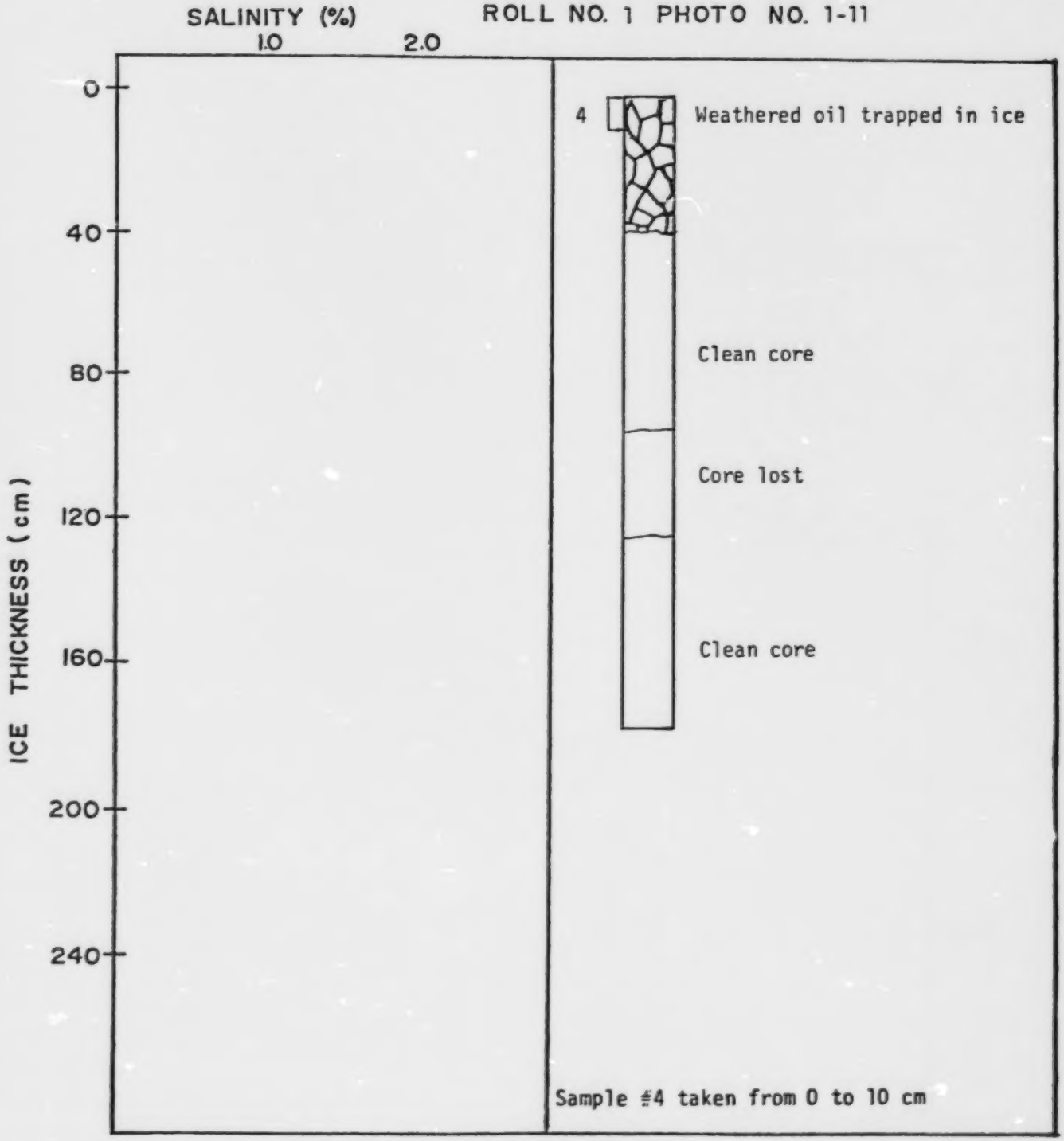
DISCHARGE NO. 2
CORE NO. 2
DATE: Sept 10, 1979
ICE THICKNESS: 2.6 m
ROLL NO. 1 PHOTO NO. 1-7 to 1-10



Sample # 3 taken from 100 to 110 cm

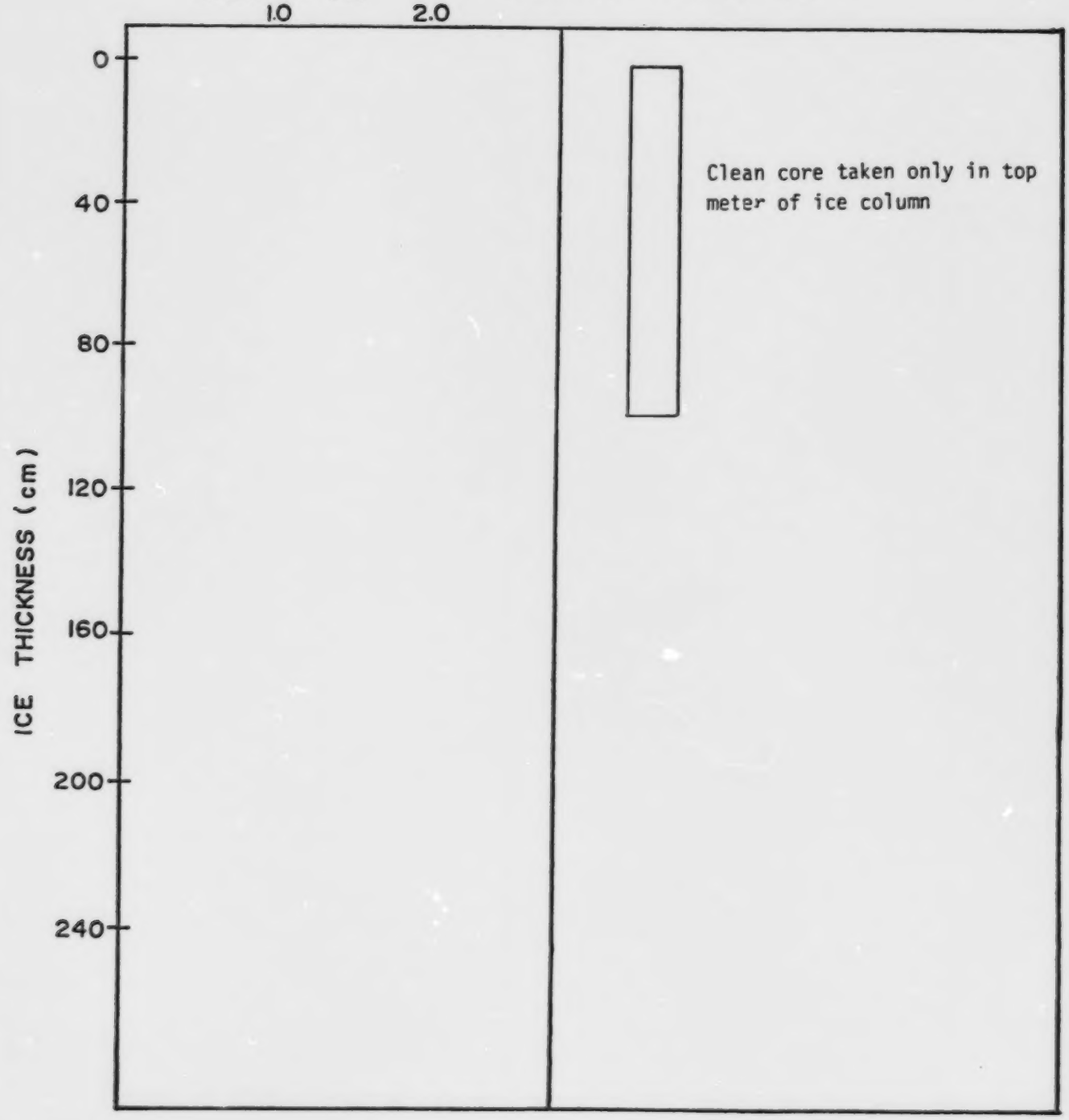
ICE CORE REPORT

DISCHARGE NO. 2
CORE NO. 3
DATE: Sept. 10, 1979
ICE THICKNESS: 1.8 m
ROLL NO. 1 PHOTO NO. 1-11



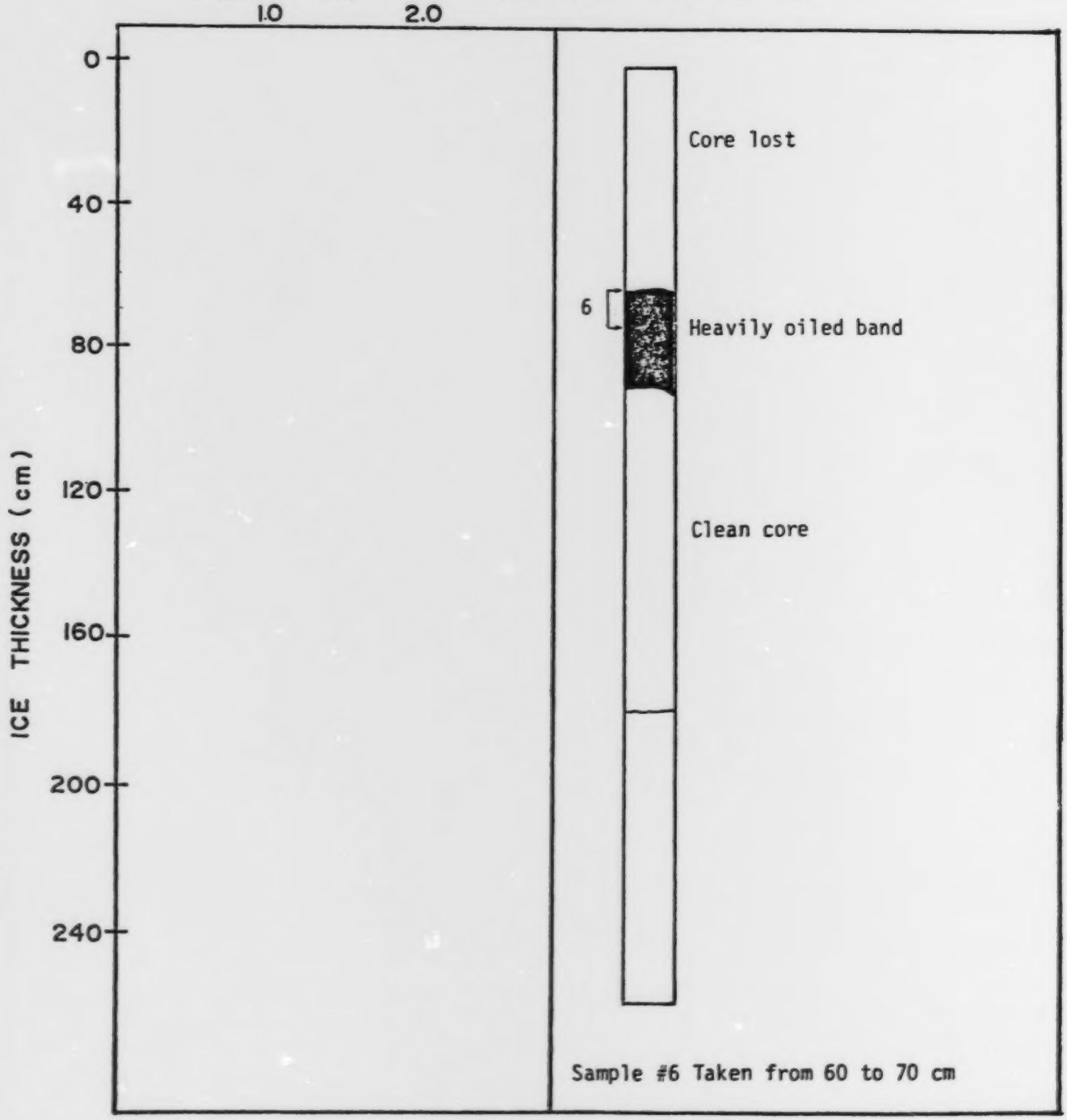
ICE CORE REPORT

DISCHARGE NO. 2
CORE NO. 4
DATE: Sept 10, 1979
ICE THICKNESS: 1 m
ROLL NO. -- PHOTO NO. --



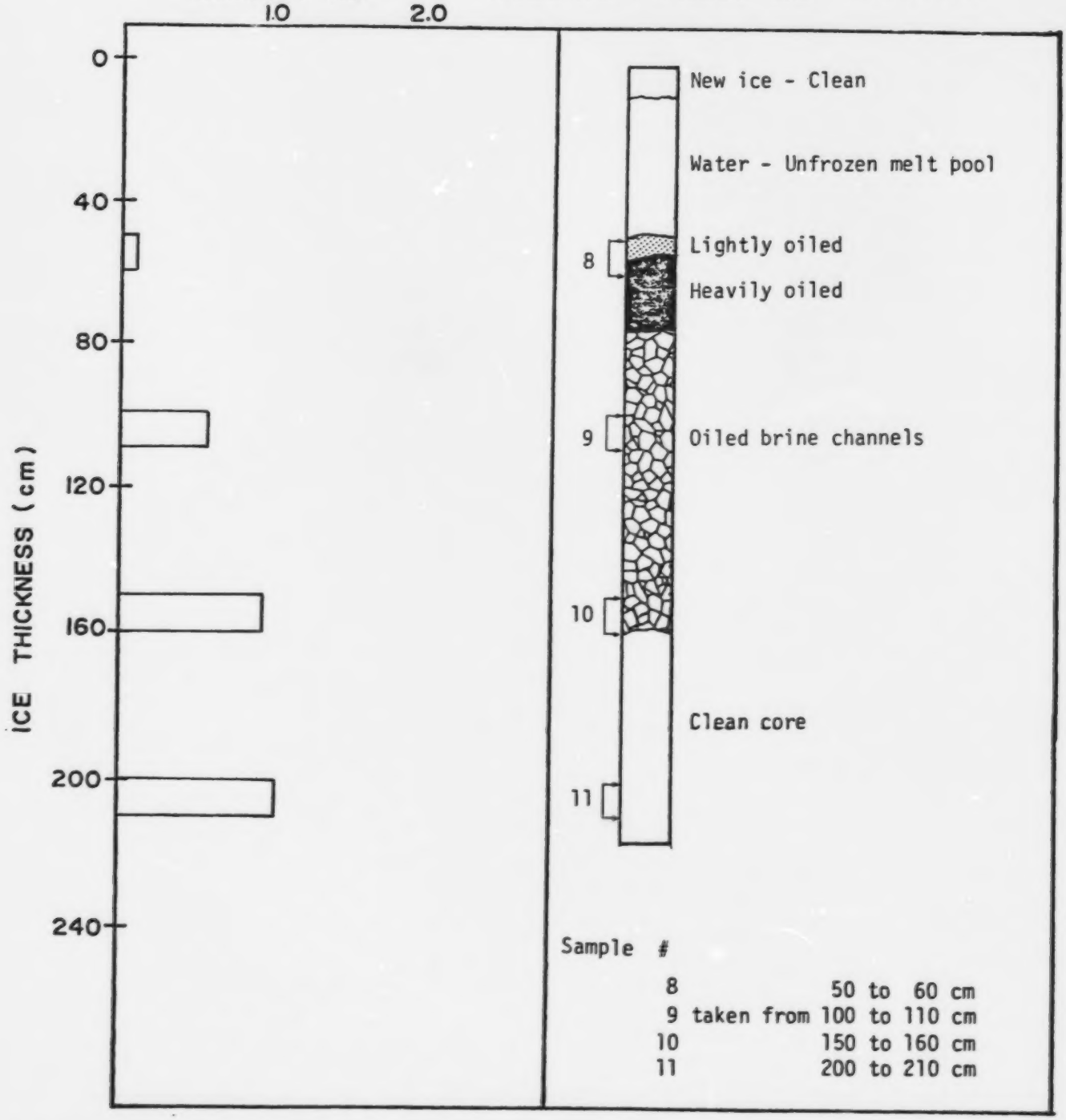
ICE CORE REPORT

DISCHARGE NO. 2
CORE NO. 5
DATE: Sept. 10, 1979
ICE THICKNESS: 1.8 m
ROLL NO. 1 PHOTO NO. 1-12 to 1-14



ICE CORE REPORT

DISCHARGE NO. 2
CORE NO. 6
DATE: Sept. 10, 1979
ICE THICKNESS: 2.2 m
ROLL NO. 1 PHOTO NO. 1-15 to 1-21

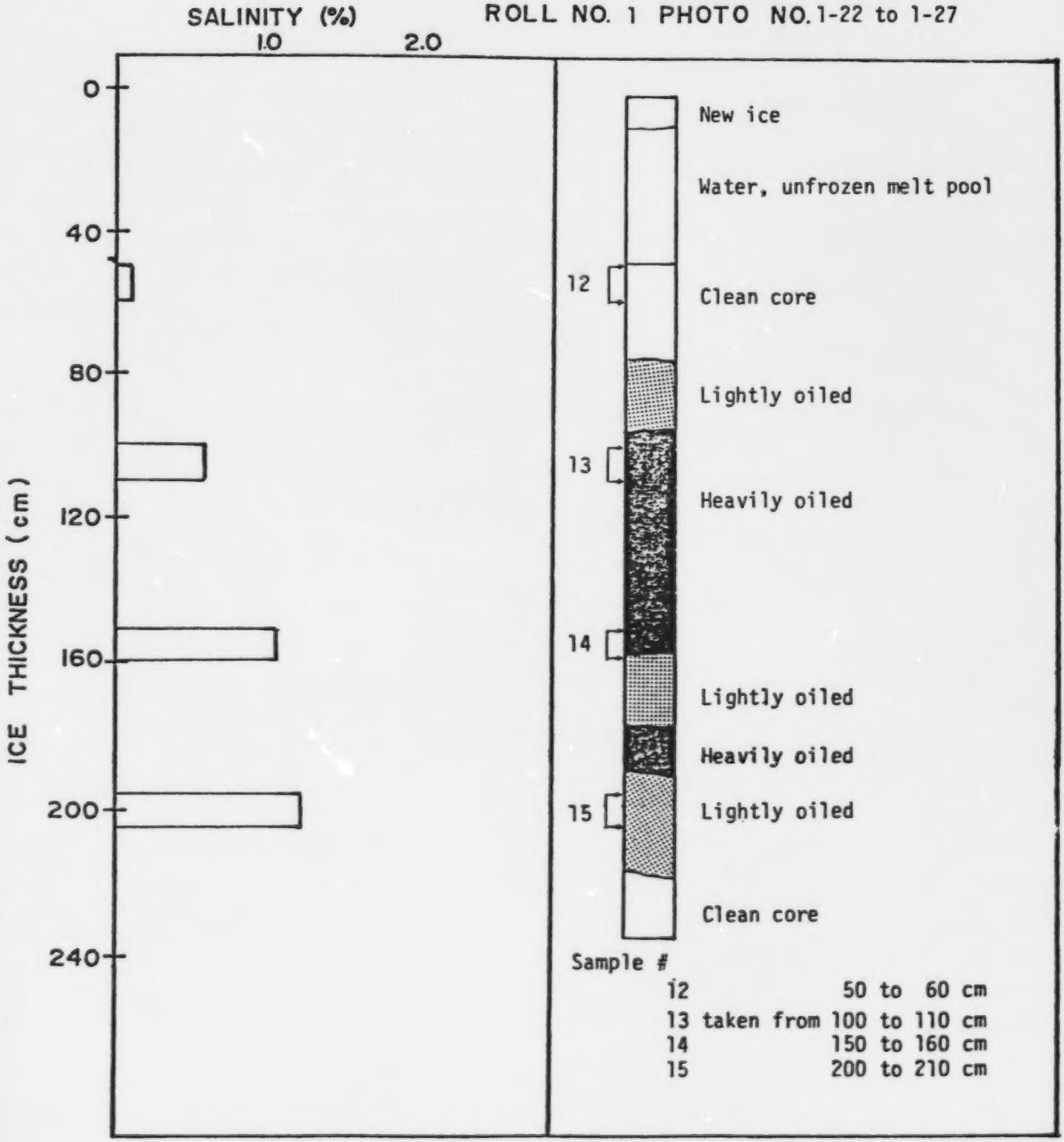


Sample #

8	50 to 60 cm
9 taken from	100 to 110 cm
10	150 to 160 cm
11	200 to 210 cm

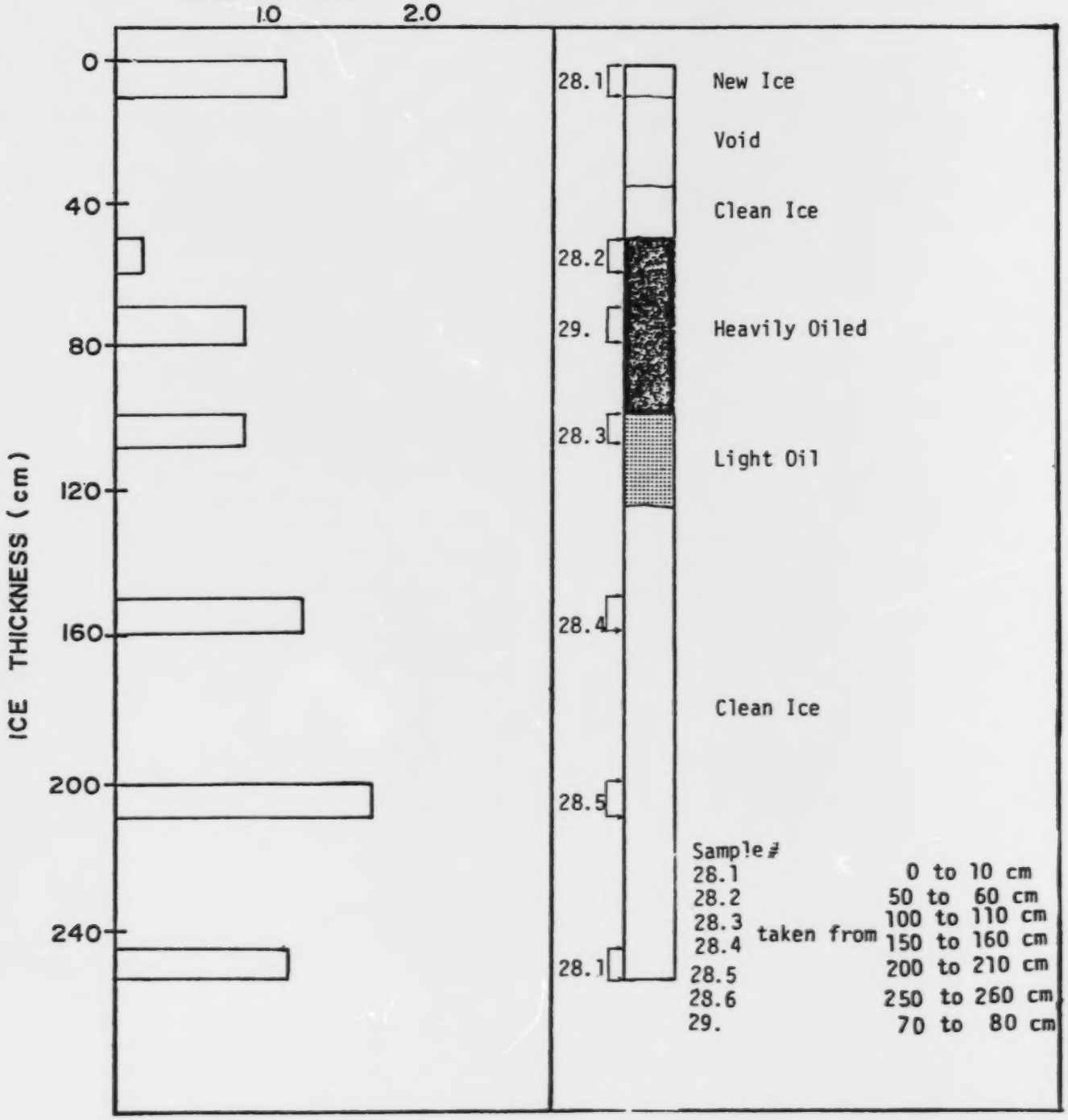
ICE CORE REPORT

DISCHARGE NO. 2
CORE NO. 7
DATE: Sept. 10, 1979
ICE THICKNESS: ~2.4 m
ROLL NO. 1 PHOTO NO. 1-22 to 1-27



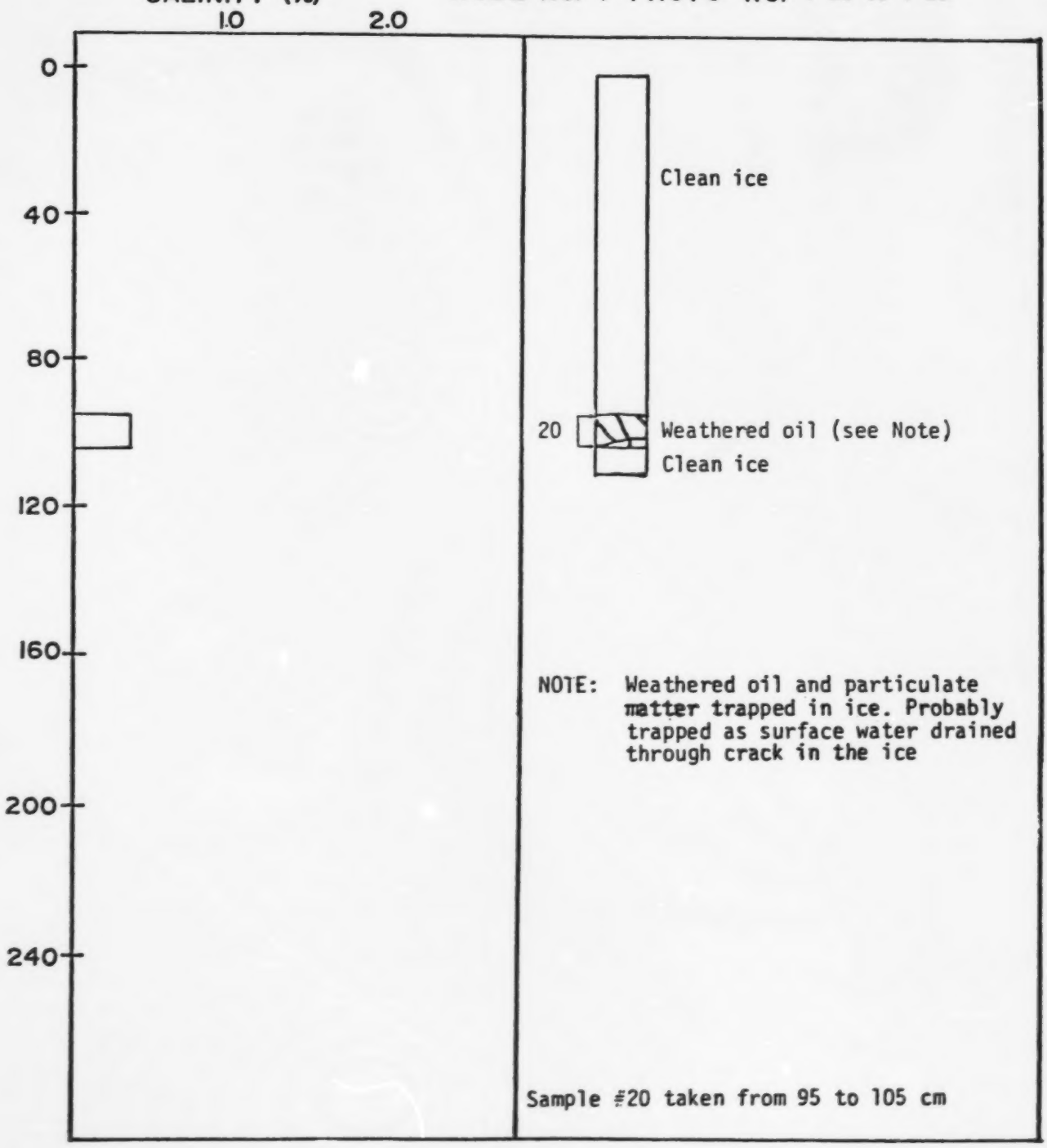
ICE CORE REPORT

DISCHARGE NO. 2
CORE NO. 1-11
DATE: September 11, 1979
ICE THICKNESS: 2.55m
ROLL NO. 2 PHOTO NO. 2-23 to 2-25



ICE CORE REPORT

DISCHARGE NO. 3
CORE NO. 1
DATE: Sept. 10, 1979
ICE THICKNESS: 1.2 m
ROLL NO. 1 PHOTO NO. 1-28 to 1-29

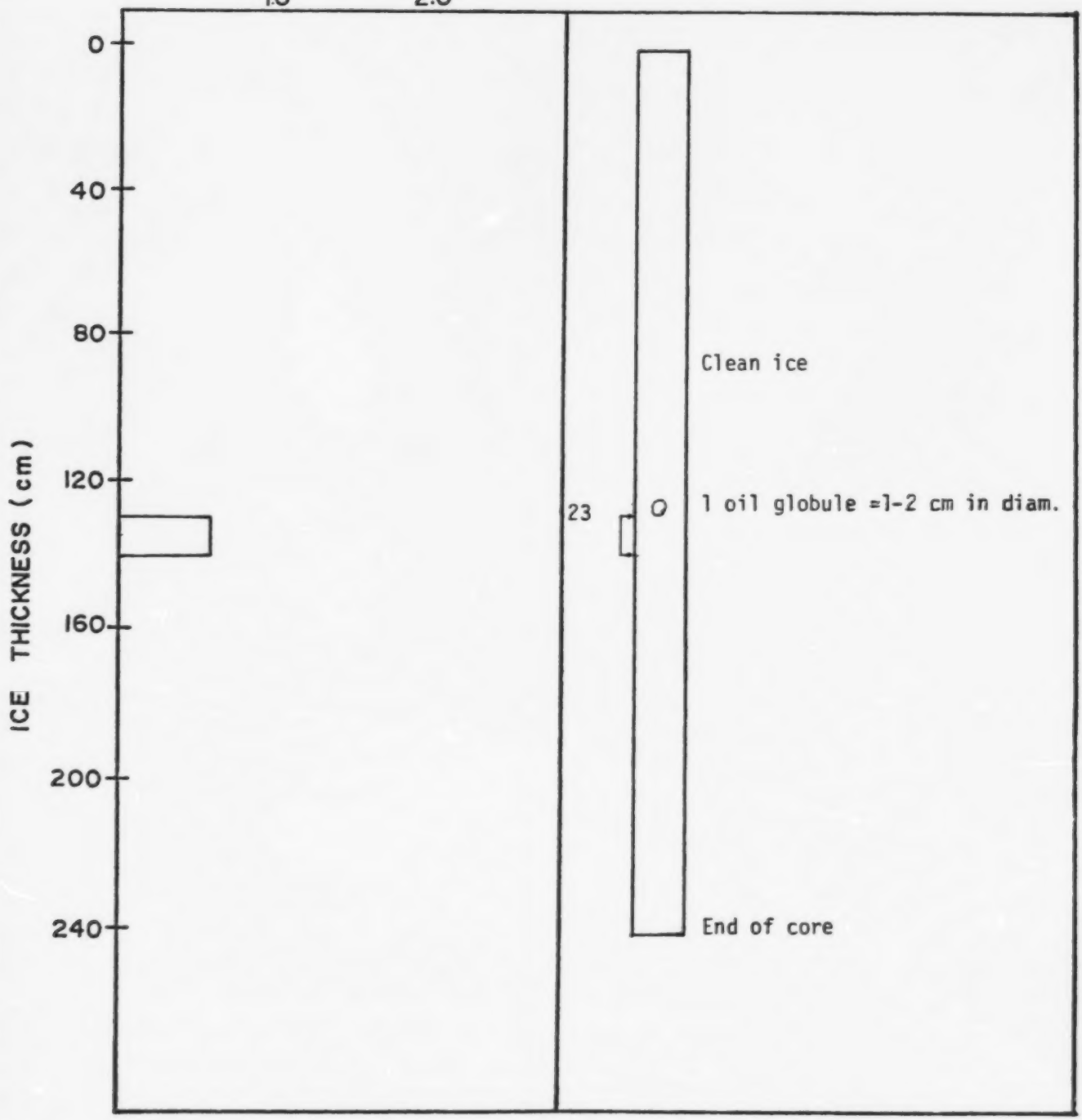


NOTE: Weathered oil and particulate matter trapped in ice. Probably trapped as surface water drained through crack in the ice

Sample #20 taken from 95 to 105 cm

ICE CORE REPORT

DISCHARGE NO. 3
CORE NO. 2
DATE: Sept. 11, 1979
ICE THICKNESS: 2.45 m
ROLL NO. 2 PHOTO NO. 2-4 to 2-5



APPENDIX II

ANALYSIS OF OIL SAMPLES COLLECTED DURING THE SEPTEMBER 9, 1979, SITE VISIT

by

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Wan Ying Shiu
Matthew Tsang

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and Applied Chemistry
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1 INTRODUCTION

Thirty-eight samples were received on November 13, 1979, from Arctec Canada Limited, consisting of polyethylene containers typically housing 300 cm^3 of water and varying quantities of oil. The objectives of the analyses were:

1. to determine and report the absolute and relative masses of oil and water for 32 of the 38 samples; and
2. to determine by gas chromatography the extent of weathering (evaporation) of 12 selected samples.

The first determination involved weighing the water, separating the oil, and extracting the remaining oil from both the water and the surfaces of the container using benzene. This benzene extract was then evaporated until most of the benzene was removed and this weight combined with the separated oil weight. It is believed that the final accuracy of this oil mass is ± 10%. In some cases, water-in-oil emulsions were formed which were either broken by heating (often with difficulty) or the relative proportions of oil and water were estimated as 75% water 25% oil. These emulsions probably formed during transportation of the samples.

The second determination involved obtaining a gas-liquid chromatogram of the oil sample taken directly and immediately from the container. The trace was then matched against traces obtained by evaporating Norman Wells crude oil to known extents.

The data obtained are given in Table 1 and copies or originals of the GC traces are included.

It should be noted that when little oil is present (e.g. < 1 g), considerable weathering may occur into the air space within the container which was typically 500 cm^3. The following approximate calculations illustrates this point.

If 1 g of oil is exposed to 500 cm^3 of air, some will evaporate. Typically, the vapour pressure of the oil is 0.1 atm; thus the 50 cm^3 of oil can vaporize into the 500 cm^3 of air. This corresponds to 50/22400 or 0.002 mols, or, if the molecular weight is 150, 0.3 g. Thus, the 1 g of oil could be reduced by 30% due to exposure to the air in the container. We can thus conclude that if less than 1 g of oil is present in the sample, no quantitative statement of the extent of oil weathering prior to sampling is possible because of sampling losses. This effect is apparent from the results (samples 26-2, 26-3, 28-2 and 28-3 all show high losses). These oils may have been fresh when sampled.

If 10 g of oil were present, one would expect proportionately less evaporation (say 3%); thus, for example, Sample 8 with 7 g of oil may have been 25% evaporated in the ice, but an additional 4% may have occurred during sampling. In this regard it is critical that if accurate extents of evaporation are required, exposure to air be closely controlled or even eliminated. We suspect that it would be erroneous to conclude from these data that oil in cores is appreciably weathered while in the ice.

2 EXTRACTION PROCEDURES AND GAS CHROMATOGRAPHIC ANALYSES

The samples were received in plastic containers. Before separating oil from water, it was possible to perform GC analyses on samples having a sufficient amount of oil layer on top of water, by carefully drawing off the oil with a syringe (Samples 6, 8, 9, 13, 14 and 29). Therefore we were able to estimate the original weathering state of the oil when it was collected, except for some loss due to the air space in the container. The oil and water portions of these samples were first separated by a 250 ml separatory funnel and their weights recorded accordingly. Benzene was used as the solvent to rinse out the residual oil from both the plastic container and the funnel and was then evaporated at about 85°C. The weight of these oil samples was added to those collected previously. Both weights were corrected for evaporation of benzene, which could be deduced from the chromatograms. Some samples were in emulsified form, i.e. "mousse"; thus it was very difficult to extract all of the oil from them. After benzene extraction, it was assumed that the remaining "mousse" contained 75% water and 25% oil.

Gas chromatographic analyses were run on a Hewlett-Packard Model 700, or 5750 equipped with a dual flame ionization detector. The electronic integrator is a Hewlett-Packard model 3380A. Sample size was 0.5 µl of oil or oil in benzene. The GC conditions were as follows:

- the columns were 3.05m long, 0.32 cm O.D. stainless steel tubing packed with 10% SE30 Ultra Phase on Chromosorb P, acid washed, DMCS treated and 60/80 mesh,
- the temperature of the injection port was 300°C and the detector was at 320°C,
- the oven temperature was held initially at 50°C for one minute after sample injection, then programmed at 15°/min until it reached 280°C for 30 minutes.

The peaks in the chromatogram are marked by hydrocarbon numbers. A series of chromatograms were prepared for Norman Wells crude oil with different degrees of weathering, i.e. 0 to 43.2% weight loss by evaporation. The chromatogram of the oil sample was then compared to estimate the degree of weathering.

APPENDIX III

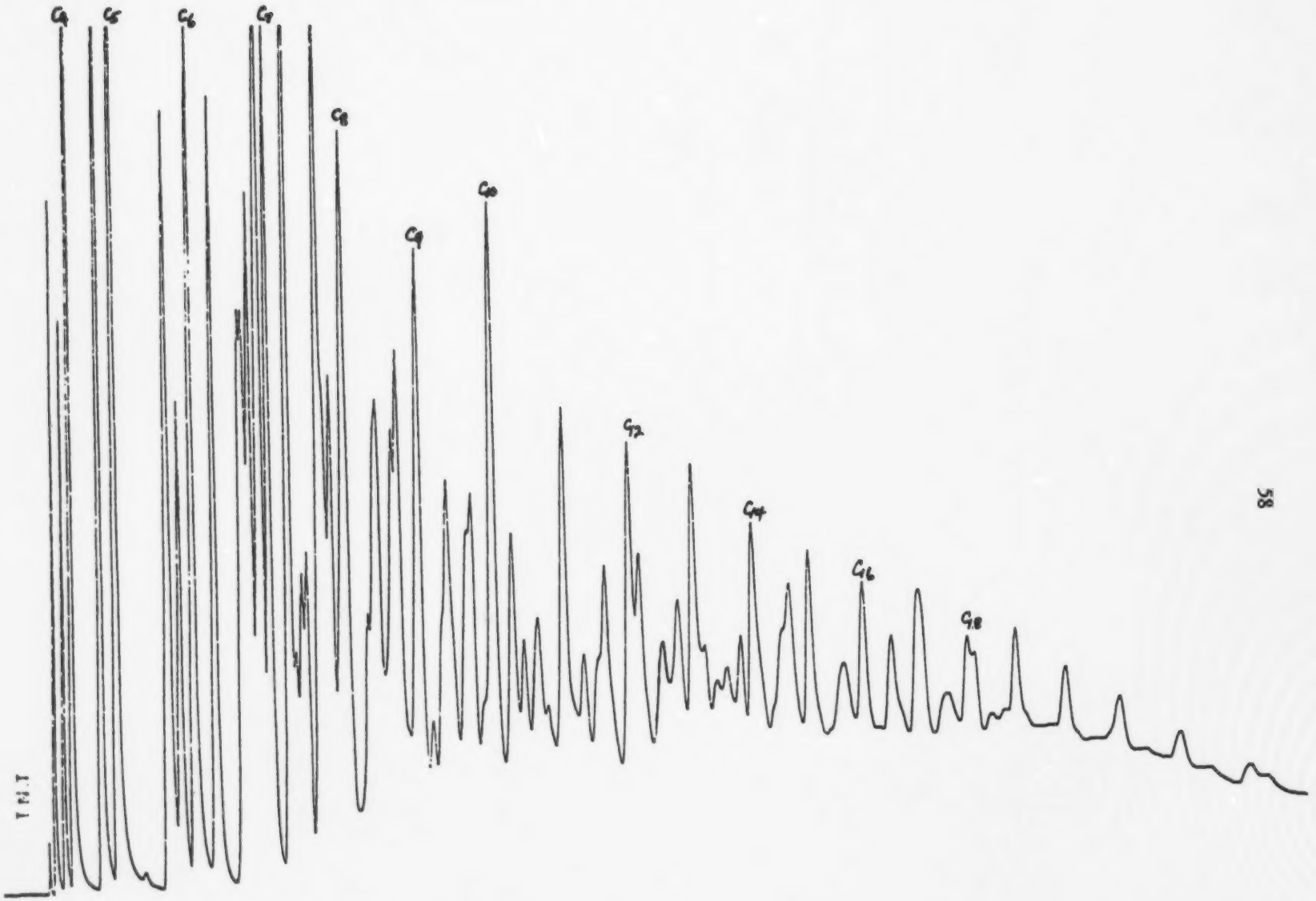
GAS CHROMATOGRAPHIC ANALYSIS OF OIL SAMPLES COLLECTED AT THE SPILL SITES DURING PREVIOUS SITE VISITS

(October 13, 1978 and March 29, 1979)

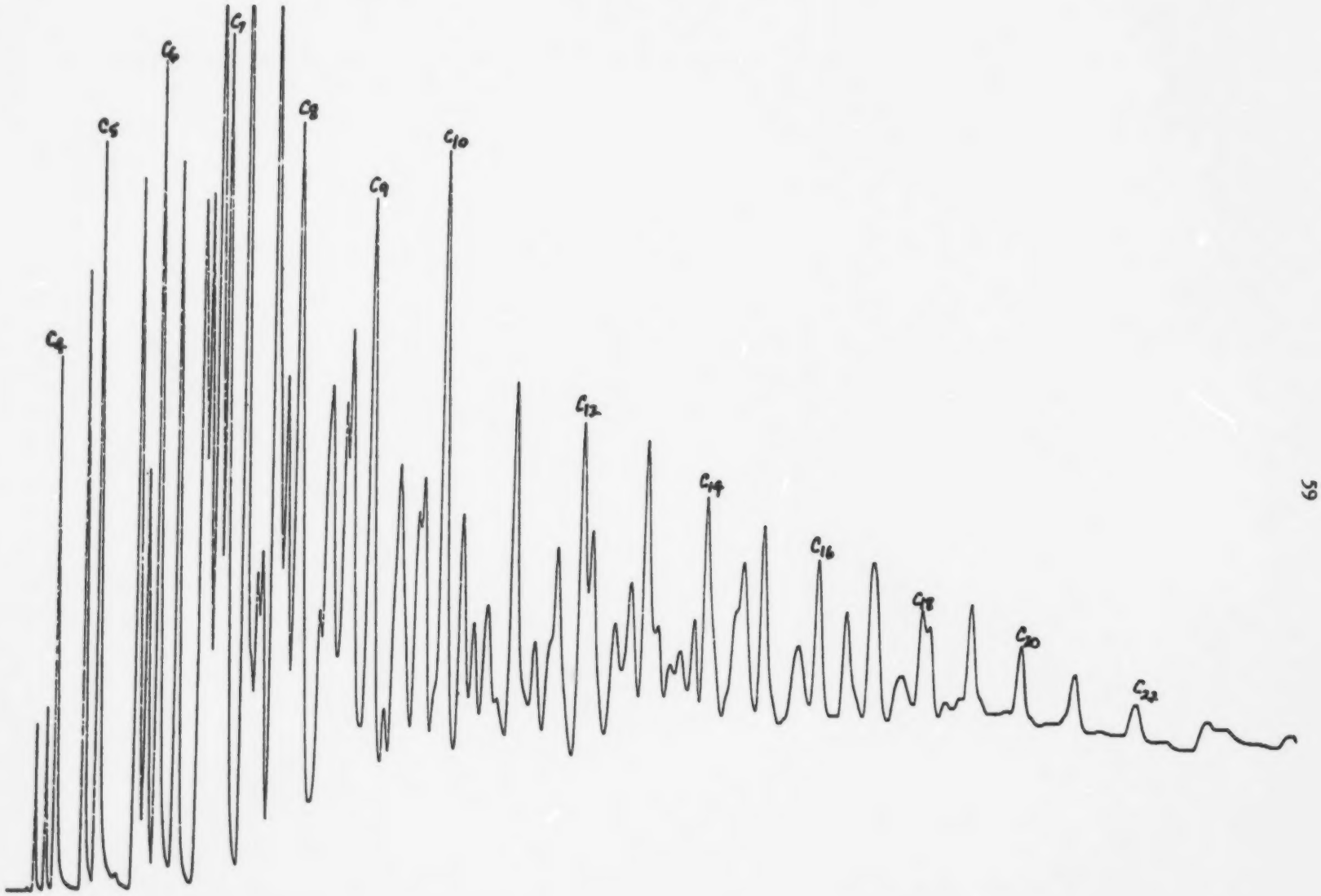
TABLE 1

Sample No.	Discharge No.	Type and Location of Sample	Mass of Water (g)	Mass of Oil (g)	Mass Percent Oil	Estimated Mass Percent Evaporated
1*	2	Oiled snow at Site No. 2	502.2	0.08	0.016	>43.2
2	2	Oiled snow at Site No. 2	-	0.07		
3	2	Band of stained ice Core No. 2 1.0-1.1 m depth	488.1	0.78	0.16	
4	2	Top of Core No. 3	347.9	2.67	0.77	
5*	2	Surface "mousse" at Loc. A (mixed with fresh snow)	488.2	23.76	4.87	~43.2
6	2	Band of ice from 0.6 m in Core No. 5	445.1	4.23	0.95	
7	2	Surface sample at Site B	412.1	32.25	7.83	
8*	2	Core No. 6 at 0.5 m depth	413.1	6.96	1.68	20
9	2	Core No. 6 at 1.0 m depth	351.0	4.71	1.34	12-15
10*	2	Core No. 6 at 1.5 m depth	371.4	5.60	1.51	20
11	2	Core No. 6 at 2.0 m depth	277.4	0.11	0.04	
12	2	Core No. 7 at 0.5 m depth	247.4	0.25	0.10	
13	2	Core No. 7 at 1.0 m depth	339.2	2.43	0.72	20
14	2	Core No. 7 at 1.5 m depth	372.8	12.45	3.34	
15	2	Core No. 7 at 2.0 m depth	201.3	0.90	0.45	
16	1	Auger cuttings, hole loc. 13.7 m from radar reflector, 30.2 m from parcol				
17*	-	Surface sample Pos. No. 2, 33.5 m from radar reflector, 42.6 m from parcol				43.2
18*	3	Surface sample from open hole				~36.7
19	3	Surface sample from open hole				
20	3	Sample of Core No. 1 at 0.95 m depth	460.0	1.63	0.35	
21	3	Surface sample of "mousse" in ice	160.2	30.79	19.22	
22*	3	Surface sample of "mousse" from open hole				~36.7
23	3	Core No. 2 at 1.4-1.5 m depth	356.8	0.061	0.017	
24	1	Auger cuttings				
25*	1	Core No. 3 at 1.0-1.1 m depth	367.9	0.46	0.13	~43.2
26-1	1	Core No. 4 at 0-0.10 m depth	216.0	0.13	0.06	
26-2*	1	Core No. 4 at 0.5-0.6 m depth	202.5	0.12	0.059	~43.2
26-3*	1	Core No.4 at 1.0-1.1 m depth	251.4	0.38	0.15	<43.2
26-4	1	Core No. 4 at 1.5-1.6 m depth	-	-		
26-5	1	Core No. 4 at 1.95-2.15 m depth	419.4	-		
27	1	Core No. 4 at 1.1-1.2 m depth (oiled lens)	393.0	0.32	0.081	
28-1	2	Core No. 1-11 at 0-0.1 m depth	91.1	0.0086	0.009	
28-2*	2	Core No. 1-11 at 0.5-0.6 m depth	268.9	0.49	0.18	~43.2
28-3*	2	Core No. 1-11 at 1.0-1.1 m depth	313.6	0.59	0.19	<43.2
28-4	2	Core No. 1-11 at 1.5-1.6 m depth	400.3	0.015	0.0037	
28-5	2	Core No. 1-11 at 2.0-2.1 m depth	280.4	0.0075	0.0027	
28-6	2	Core No. 1-11 at 2.5-2.6 m depth	455.9	0.0043	0.0009	
29	2	Core No. 1-11 at 0.7-0.8 m depth (oiled lens)	361.7	2.24	0.62	

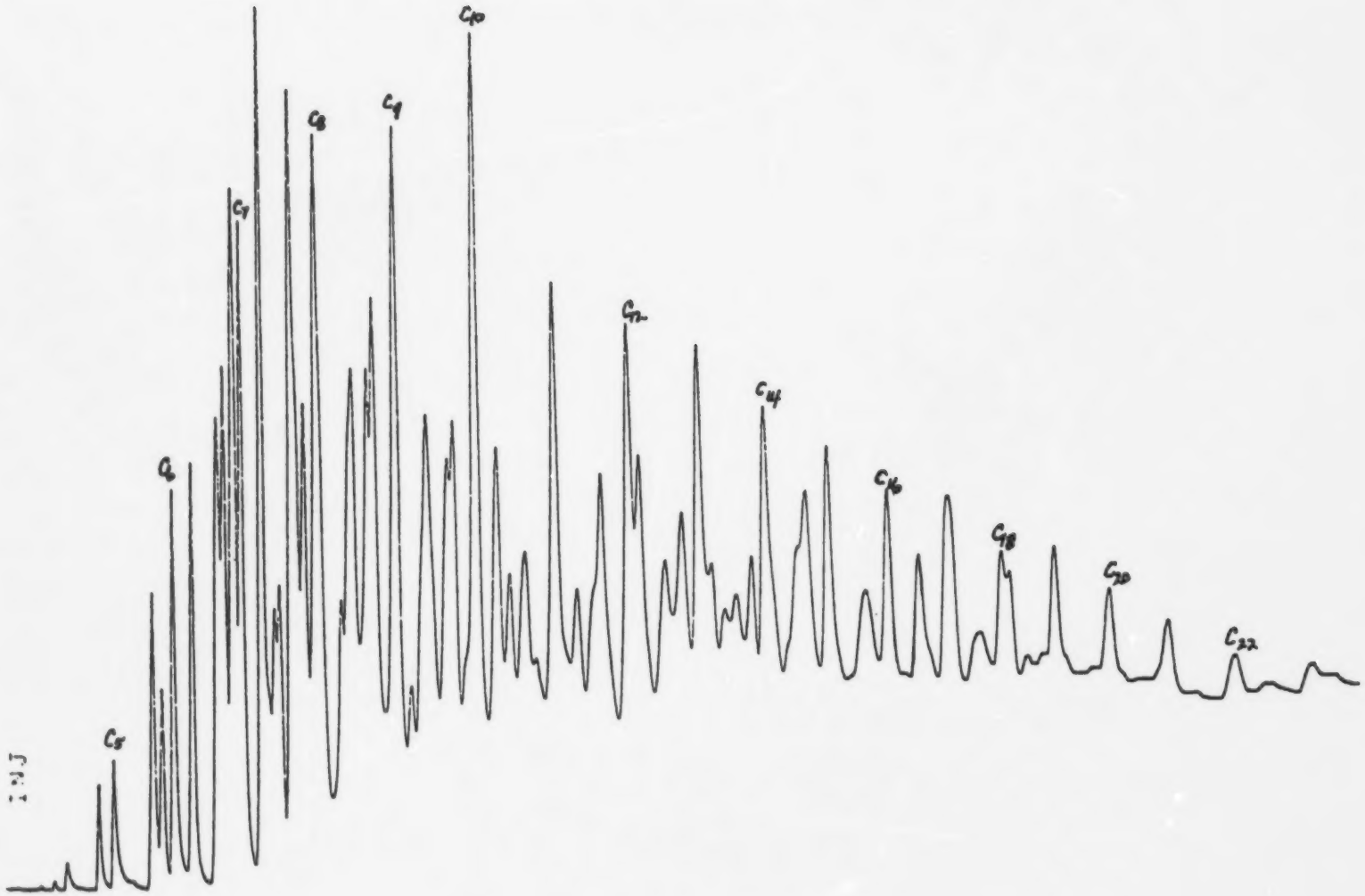
* Denotes Gas Chromatograph Analysis done on sample.



GAS CHROMATOGRAM FOR FRESH NORMAN WELLS CRUDE OIL (0% EVAPORATED)



GAS CHROMATOGRAM FOR 6% EVAPORATED NORMAN WELLS CRUDE OIL



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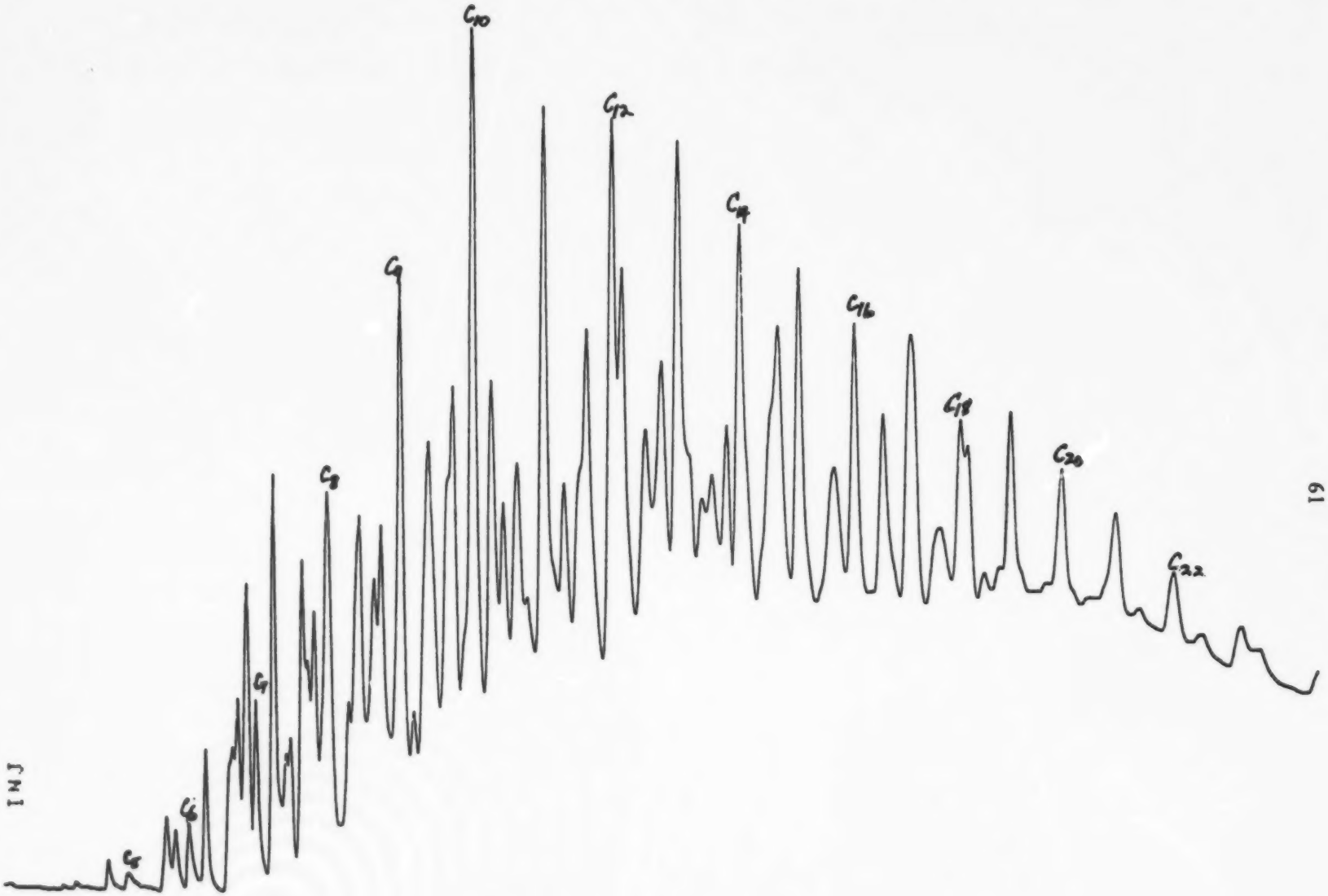

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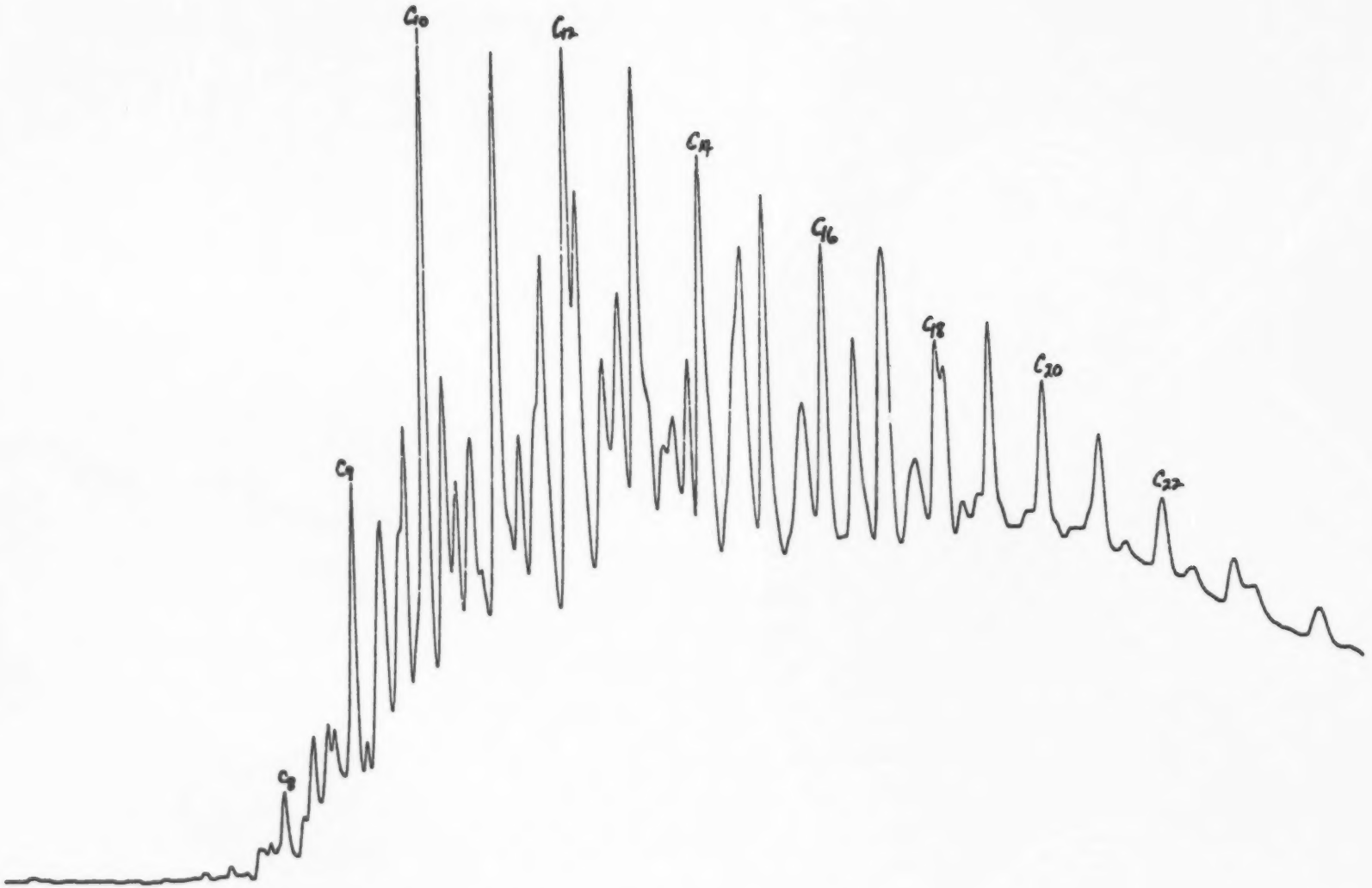
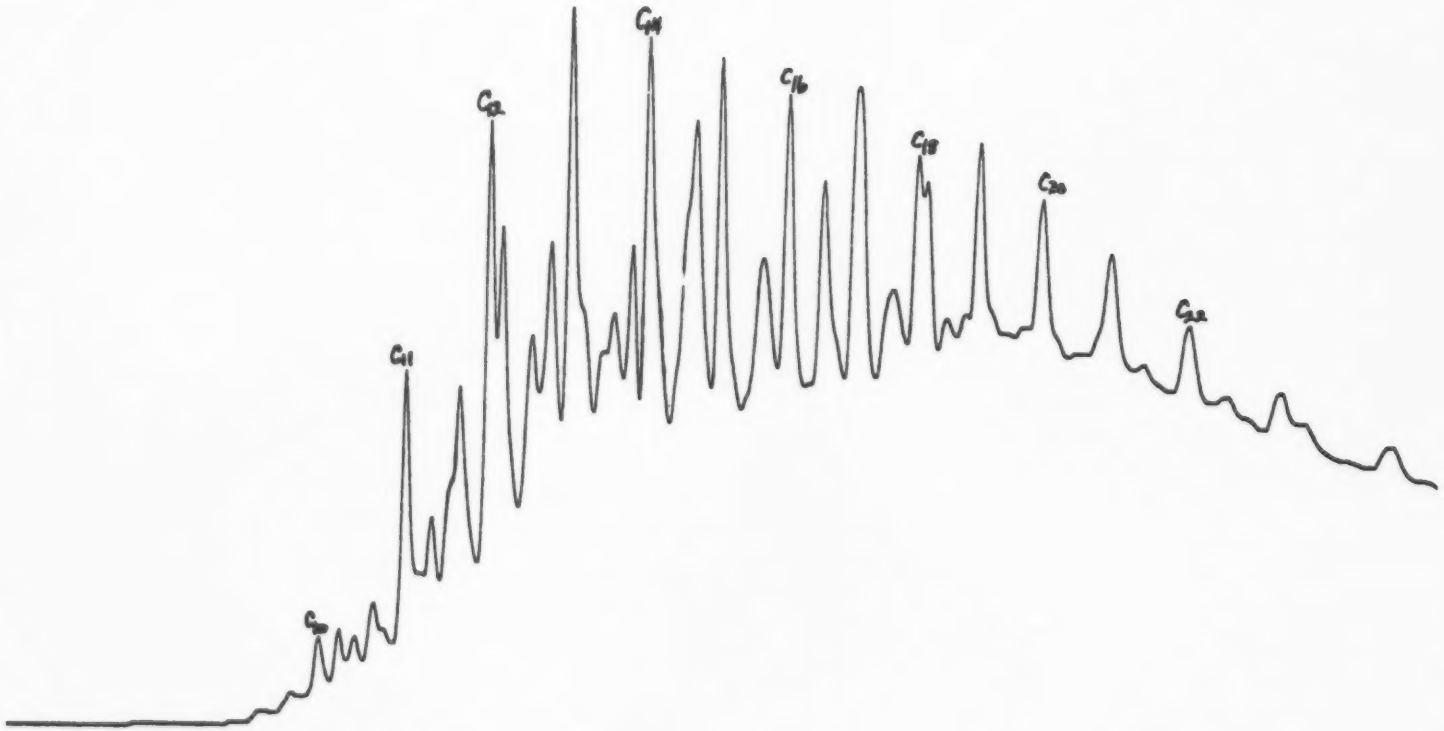
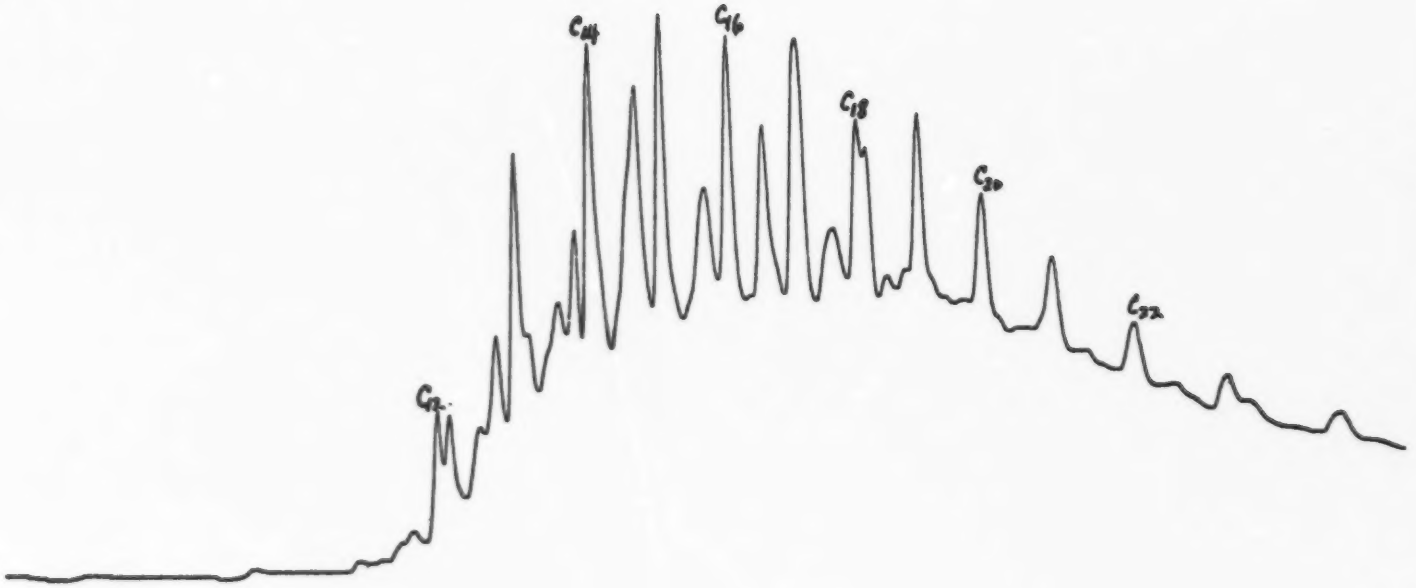


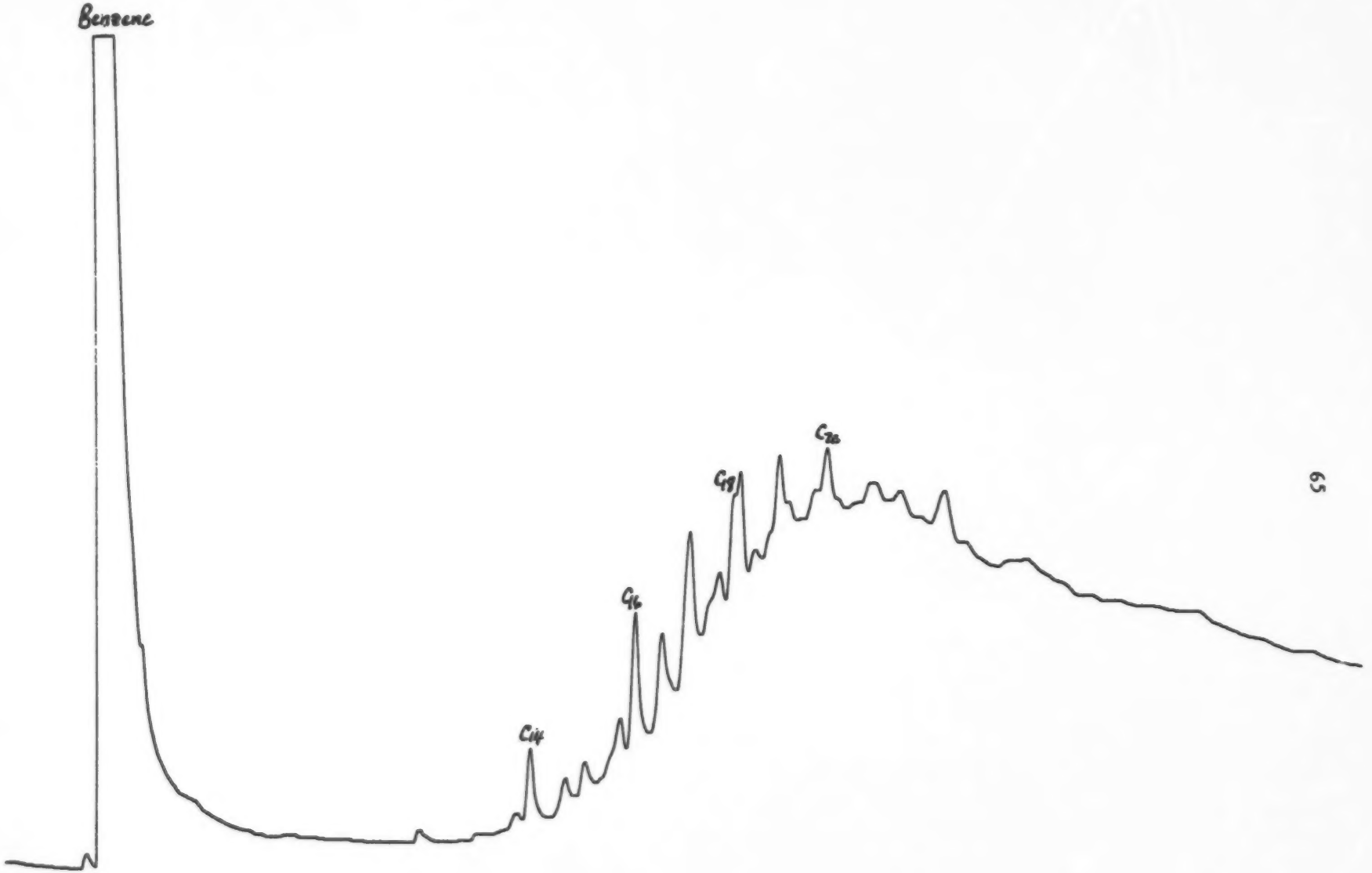
GAS CHROMATOGRAM FOR 29% EVAPORATED NORMAN WELLS CRUDE OIL



GAS CHROMATOGRAM FOR 36.7% EVAPORATED NORMAN WELLS CRUDE OIL



GAS CHROMATOGRAM FOR 43.2% EVAPORATED NORMAN WELLS CRUDE OIL



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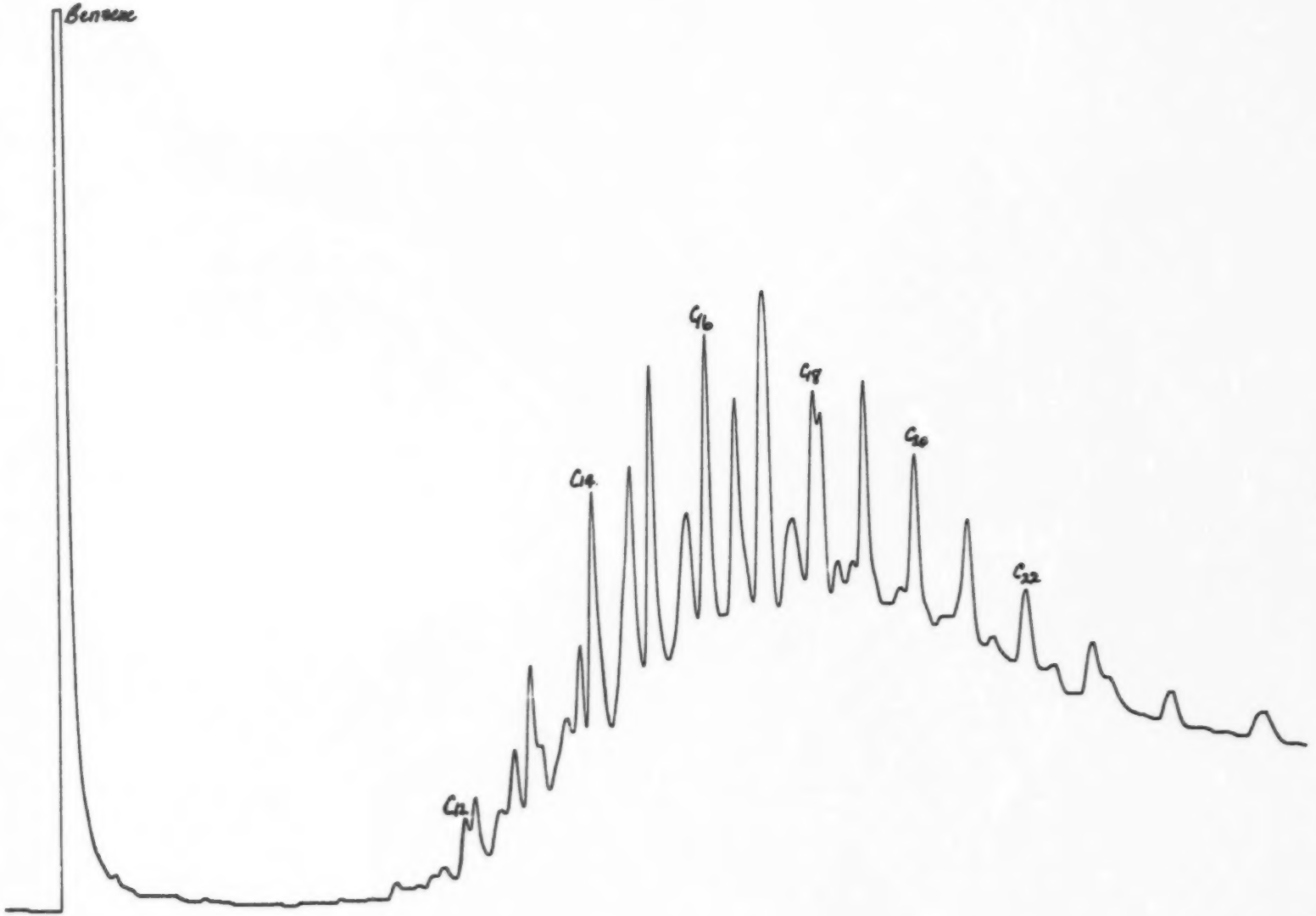

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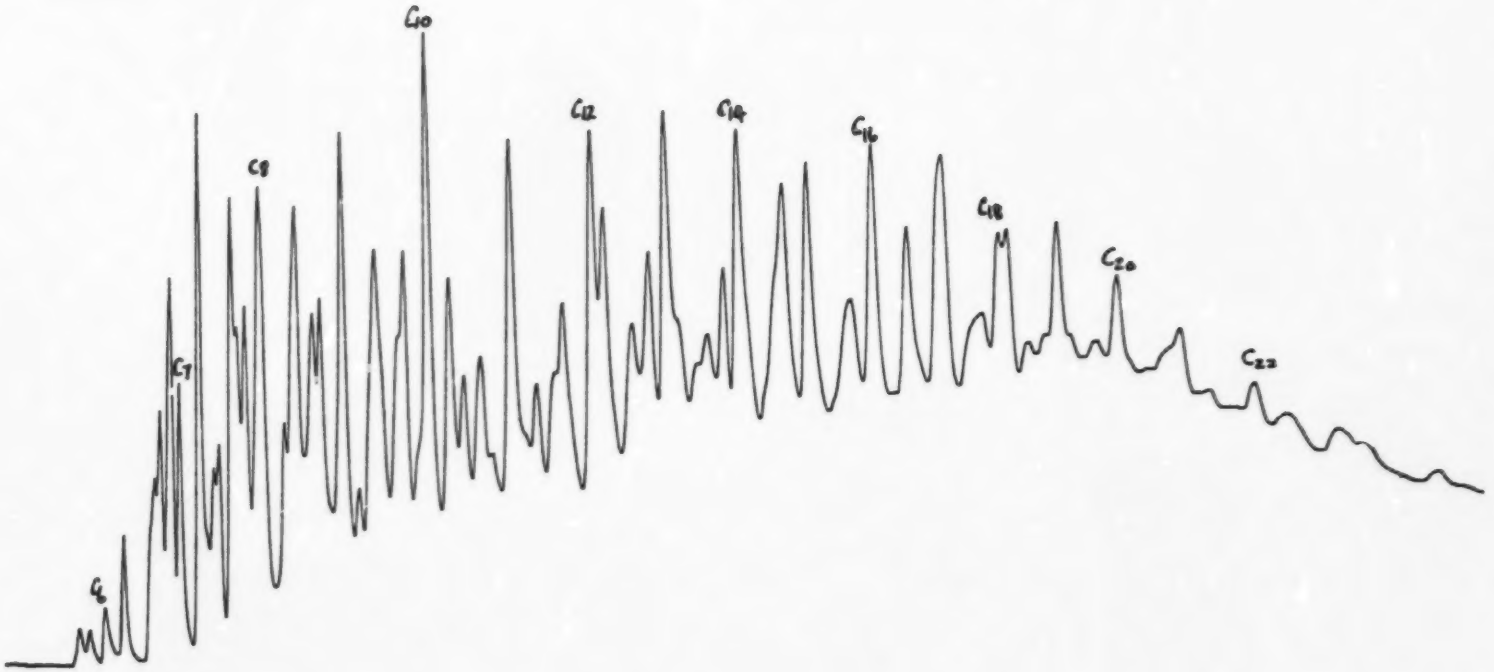

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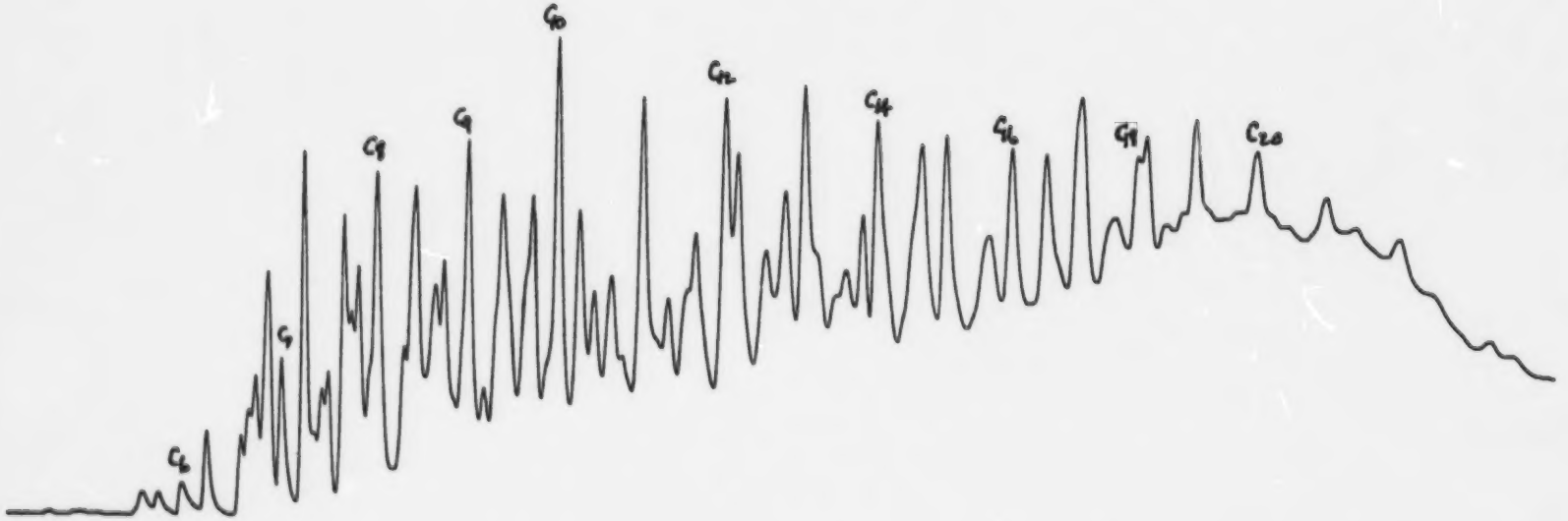

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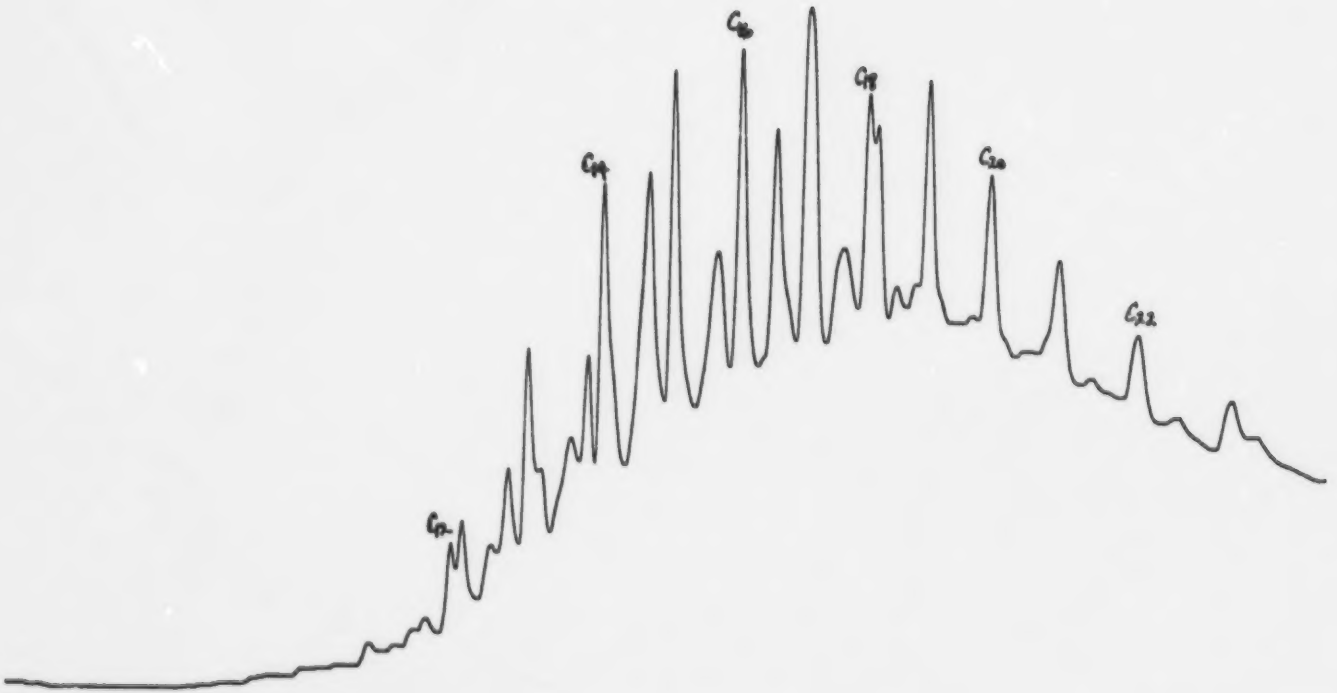

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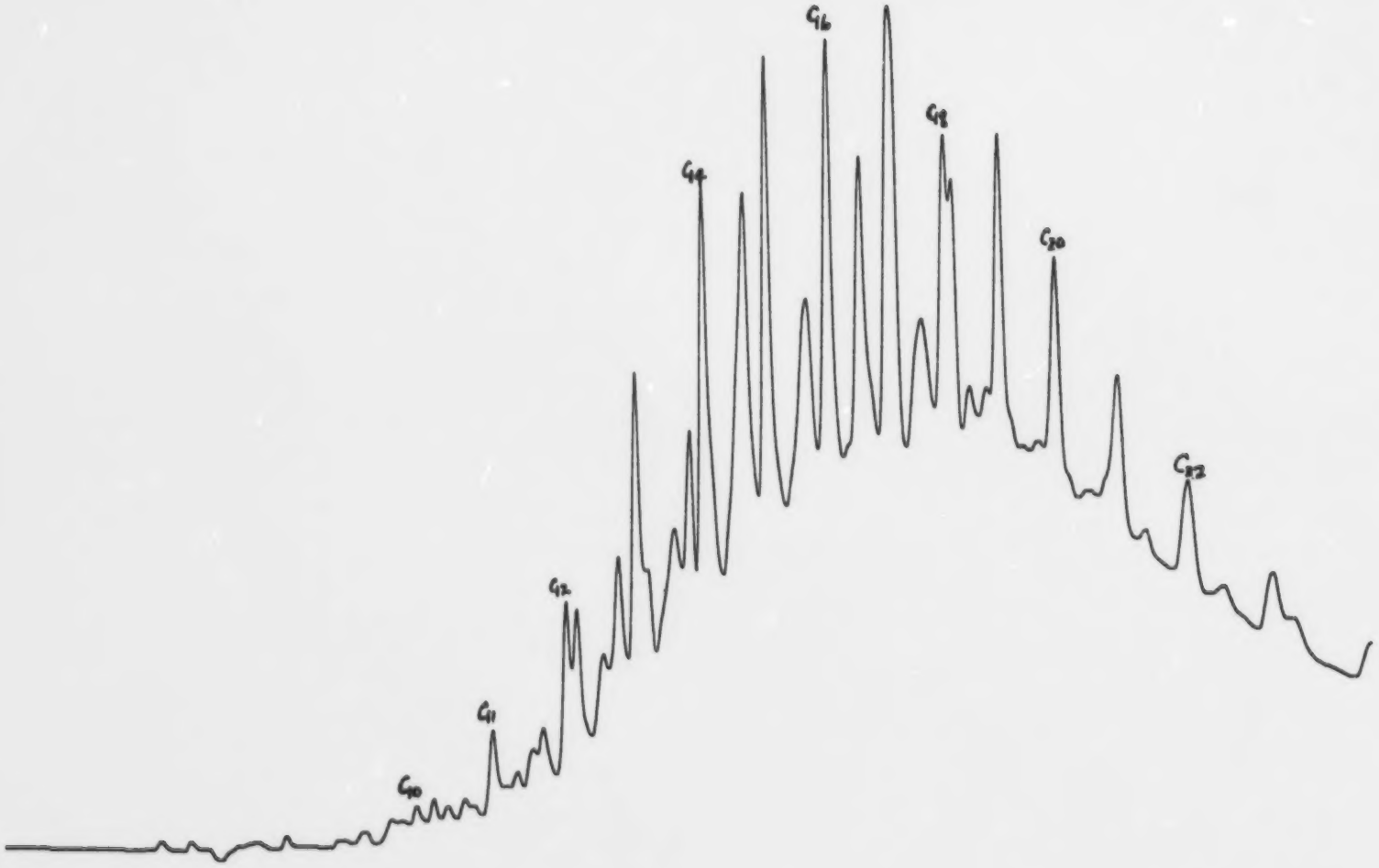

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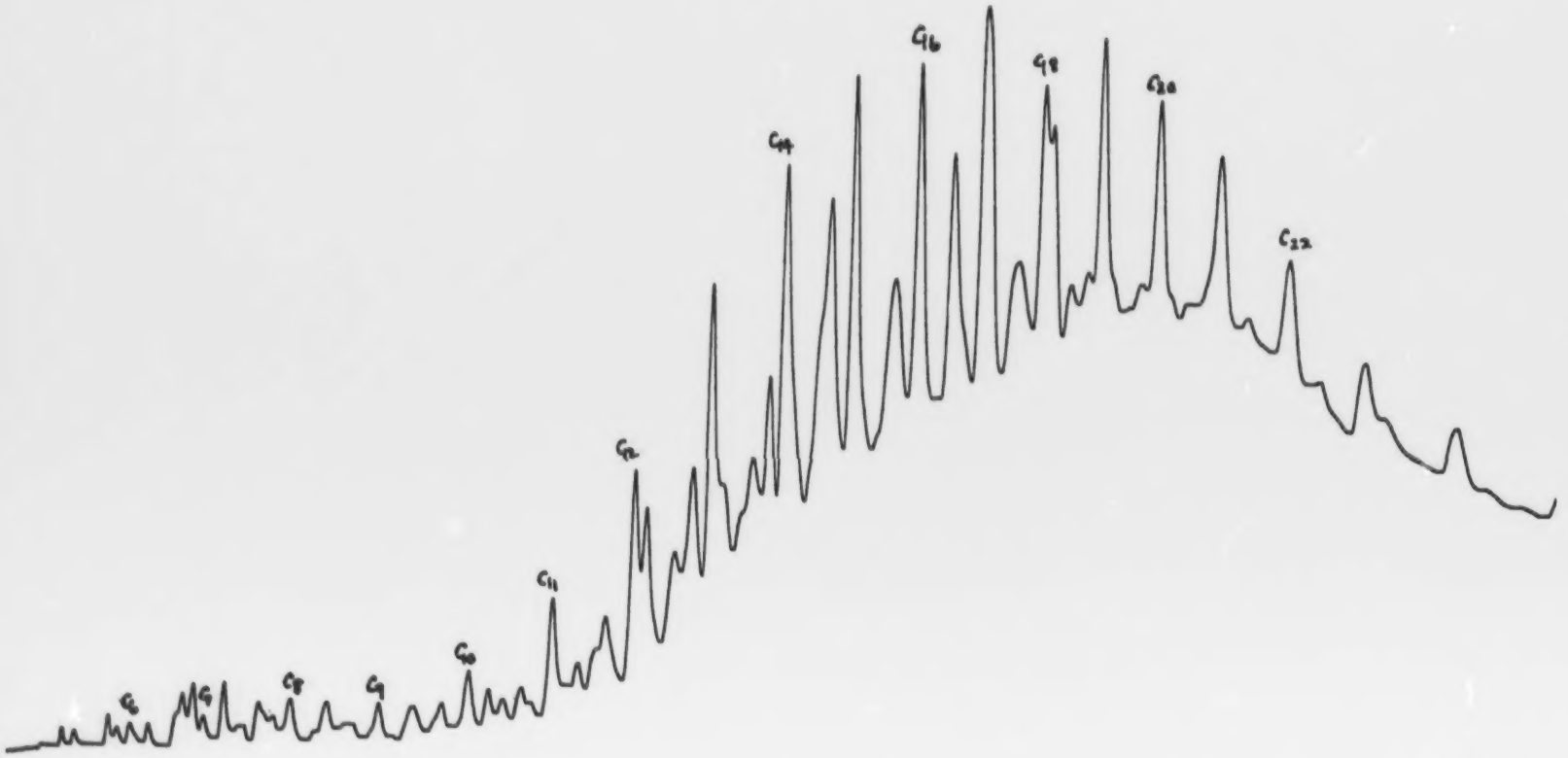

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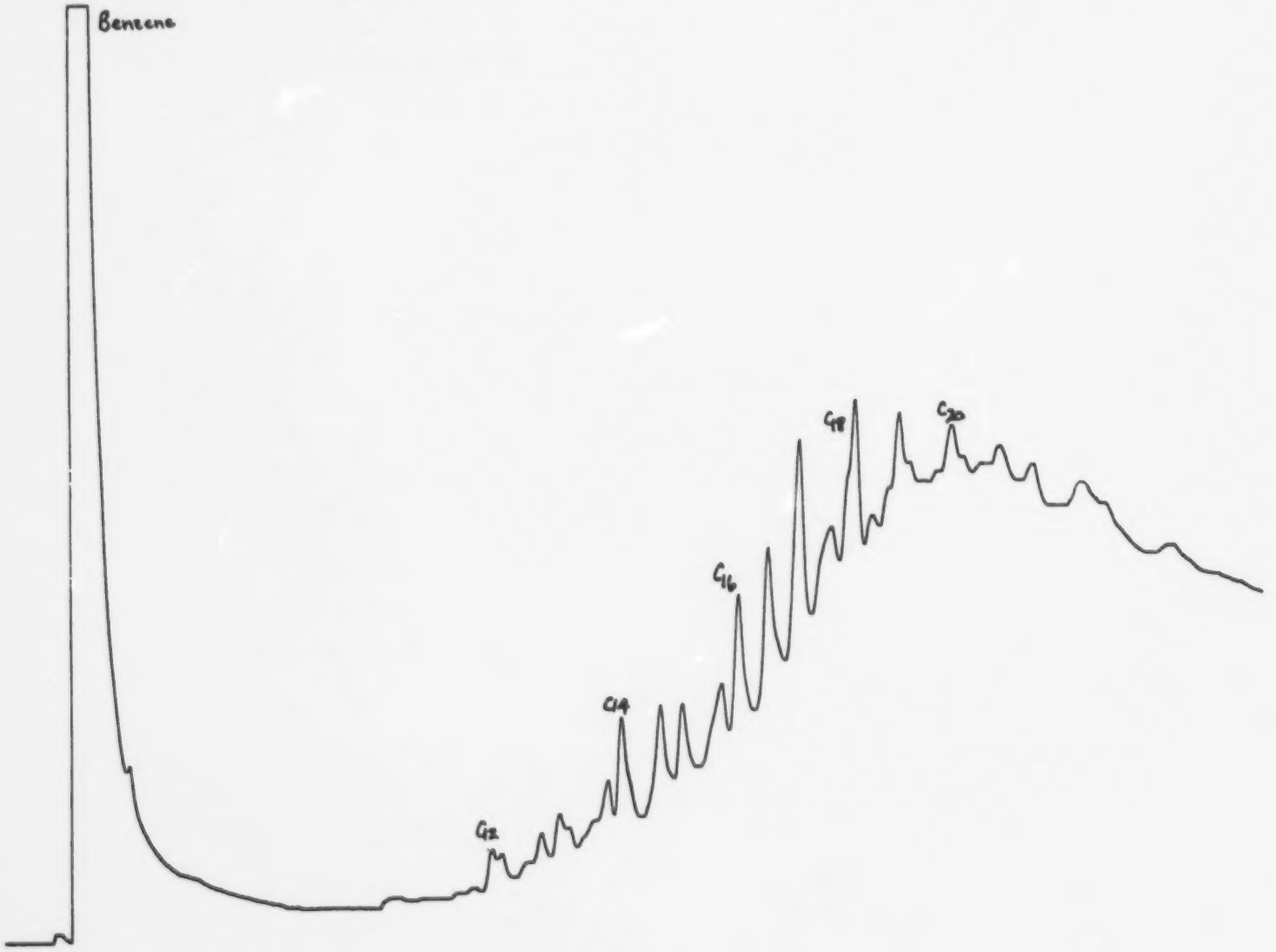

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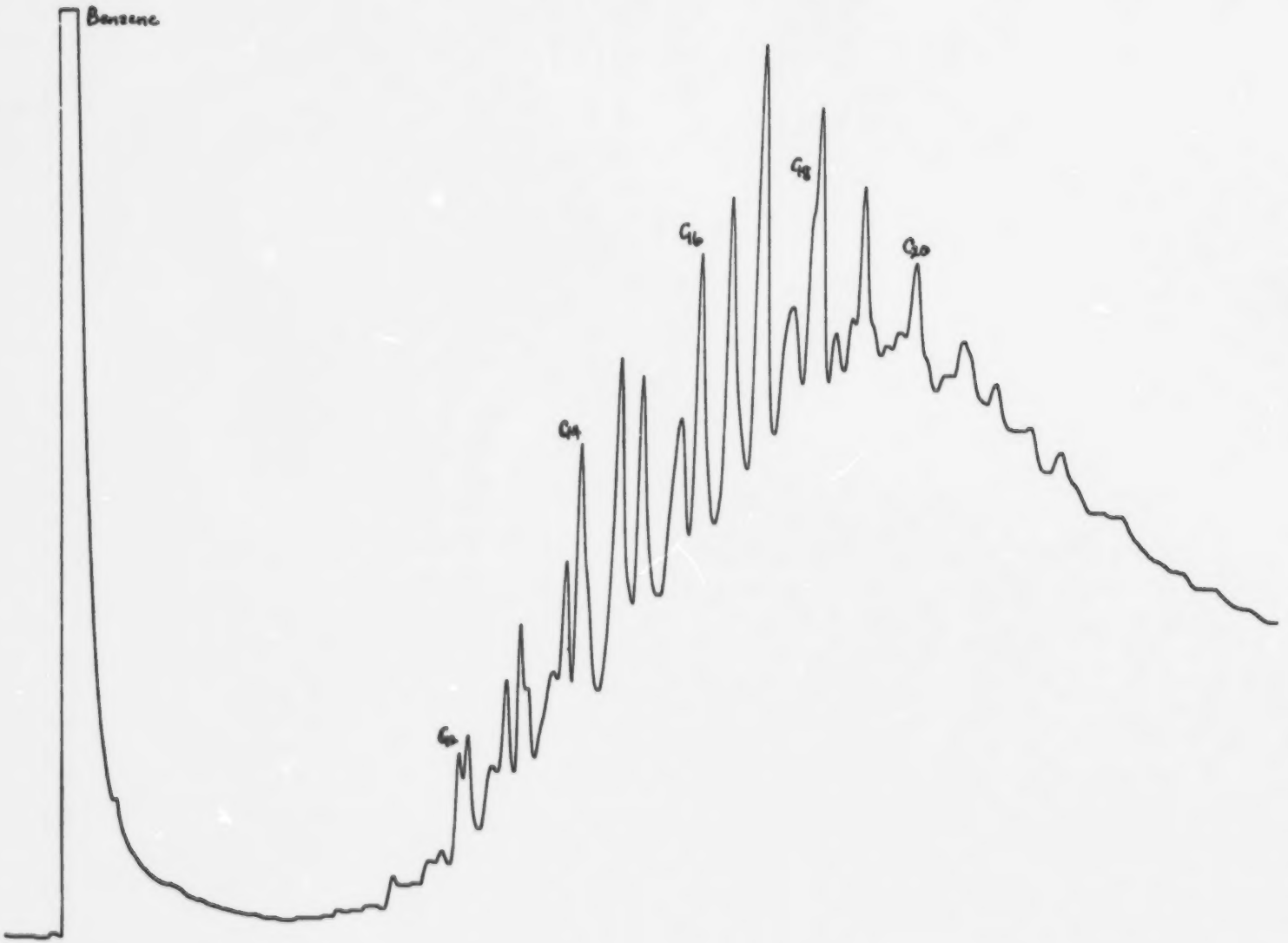

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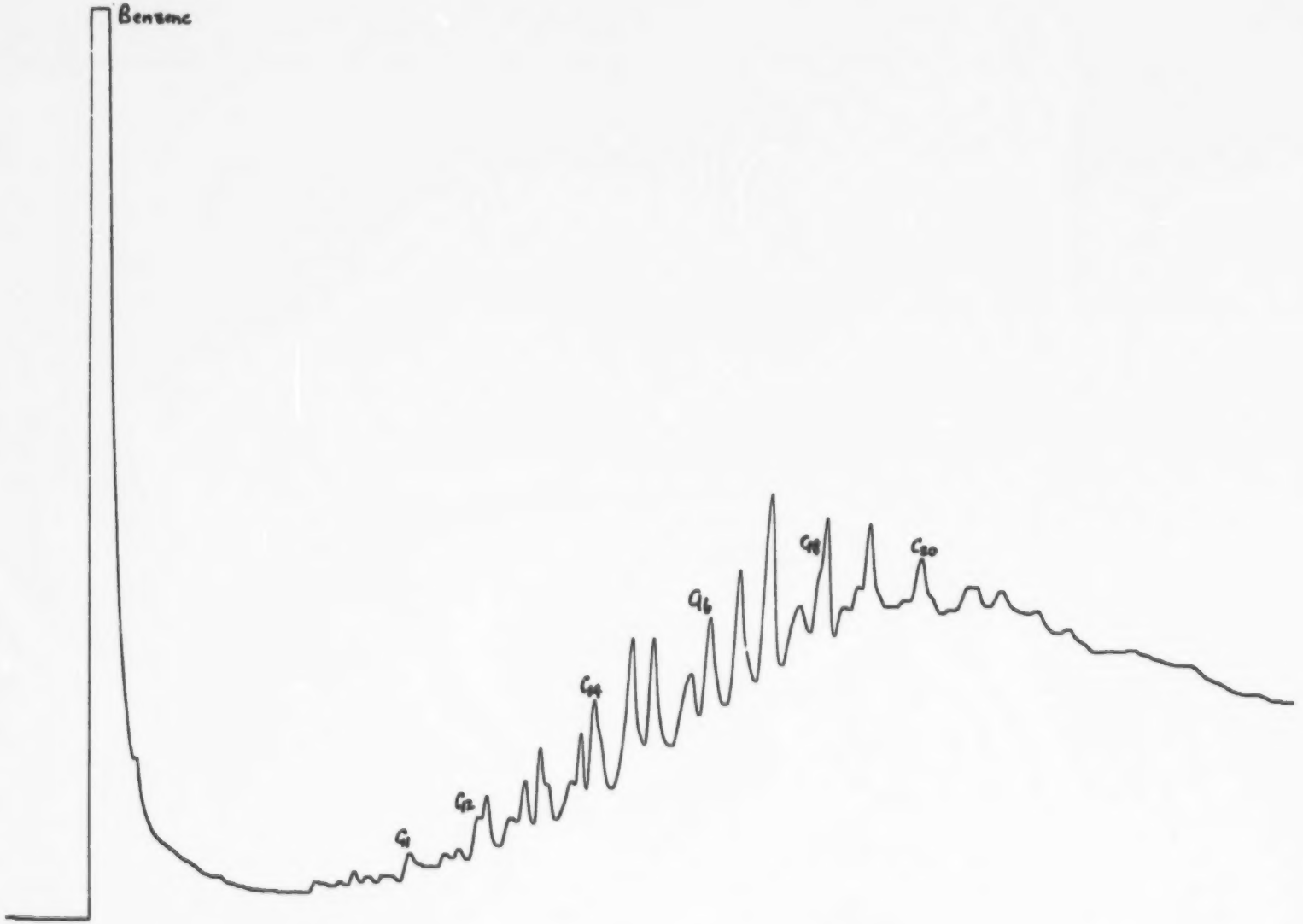

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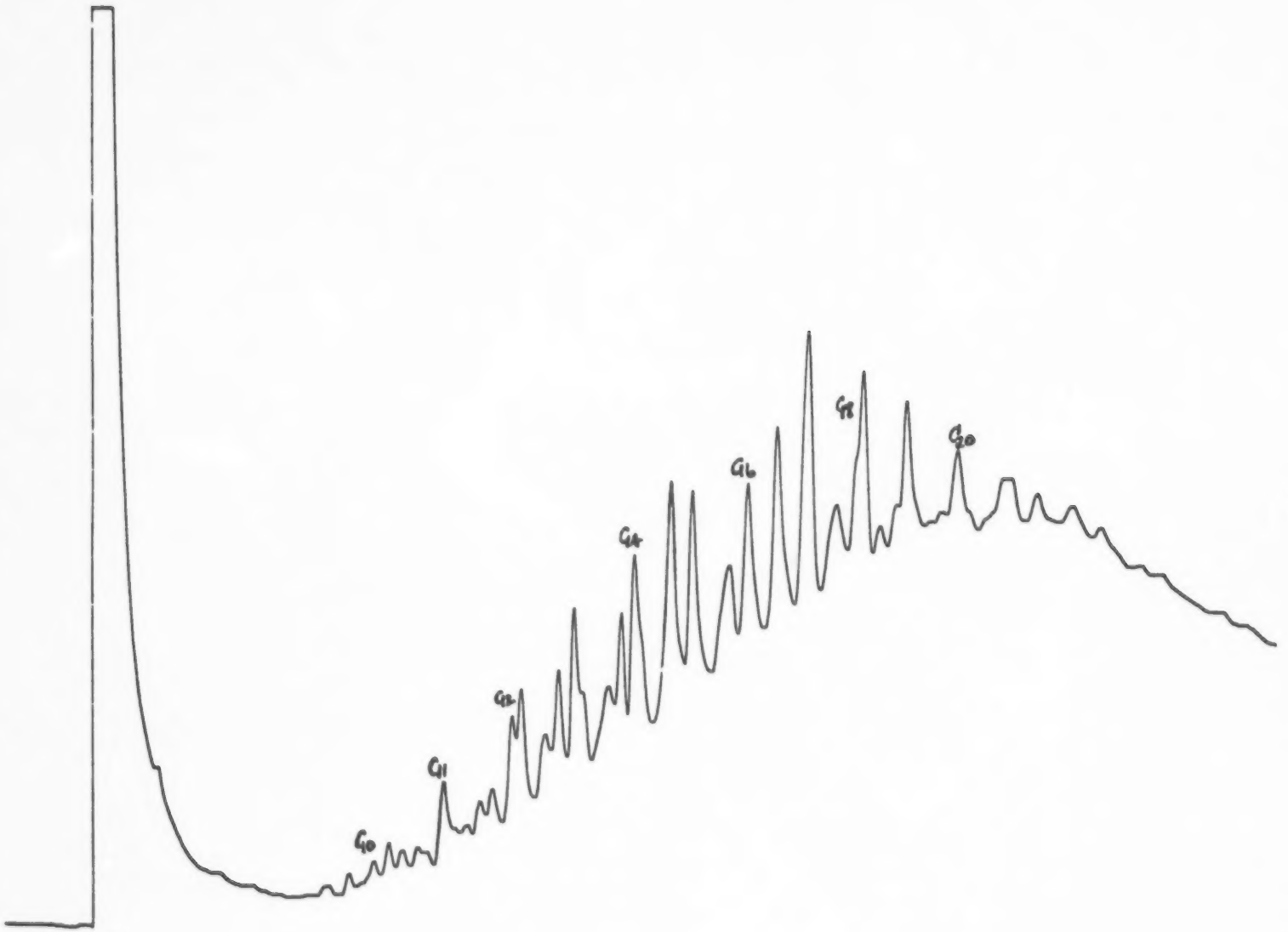

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